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THE LINEAR ELECTRON ACCELERATOR

by D. W. FRY *).

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Much of the work of contemporary nuclear physicists depends on the use of beams of high energy particles which are available from the particle accelerators constructed during the past two decades. Further development of techniques for producing such beams is directed towards higher particle energies as well as towards larger particle beam currents: higher energies are essential for discovering new types of reactions or elementary particles hitherto unknown, large currents are indispensable for certain investigations involving rather weak interaction effects, as for example neutron scattering.

The production of high energy electrons, in the millions of volts range, is of great importance also in another realm, medicine. The very penetrating X-rays emitted from targets under such electron bombardment give rise to dose distributions inside the human body which from a physical point of view should be much more favourable for effective therapeutic treatment than can be obtained with the 200 or 400 kV X-rays commonly used. Again, high X-ray intensities and, therefore, large electron beam currents are of prime importance for successful medical applications.

A very efficient means of meeting the demand for intense beams of electrons of several millions of volts energy, has been found in the linear electron accelerator. A series of articles on this development will be published in this Review within the next couple of years. The editors are greatly indebted to Mr. Fry, one of the most eminent authorities in the world in this field, for his permission to publish the following paper as the first in the projected series. Mr. Fry, who is at present Head of the General Physics Division of the British Atomic Energy Research Establishment, was at the head of the group of workers who built the very first travelling wave type linear electron accelerator.

*This paper is a slightly altered and shortened version of a lecture delivered at a symposium on Particle Accelerators at Delft in February 1951 **) and gives a brief account of the fundamentals of the linear electron accelerator. The following articles of the series will describe i.a. the accelerators for 4 and 15 MeV respectively that were built by the Mullard Research Laboratory at Salfords (Surrey, England) under the direction of Dr. Bareford, in close collaboration with Mr. Fry's groups at Harwell and Malvern.*

Introduction

Since about the time Cockcroft and Walton [1]) disintegrated the lithium nucleus by bombarding it with alpha particles accelerated in a cascade generator to 800 keV, many ways have been proposed for accelerating particles to high energies. Some, such as the resonant transformer, the electrostatic generator, and the cascade generator, establish the full accelerating field between an insulated electrode and earth. They may be designed to have extremely useful properties such as high beam intensities and in the case of the electrostatic and cascade generator a very narrow energy spectrum, but very formidable engineering problems are encountered if an attempt is made to design them for more than a few million volts energy.

To overcome the high potential insulation difficulty several alternatives were proposed, all of which in one form or another made use of the repeated action of quite low voltage fields upon the particles to be accelerated. Accelerators like the cyclotron, the betatron, the synchrotron and the synchrocyclotron which accelerate particles in cyclic paths under the action of magnetic and oscillating electric fields and which use frequencies up to a few tens of Mc/s form one broad group, whilst the methods in which the particles are accelerated in a straight line by either the continuous or intermittent action of (ultra) high frequency fields form another group. The latter principle was used successfully by Wideröe [2]) in 1928 to accelerate potassium ions to 50 kV with a maximum applied voltage of 25 kV and a few years later by Sloan working first with E. O. Lawrence [3]) and then with Coates [4]) to accelerate mercury ions to 1.26 and 2.85 MeV respectively. Beams working with Snoddy [5]) and with Trotter [6]) also accelerated particles in a straight line using a different technique from Sloan et al. In their method co-linear electrodes were connected to the appropriate points of loaded transmission lines along which were transmitted voltage impulses. Protons and electrons were accelerated to energies of a few million volts by this method.

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*) Atomic Energy Research Establishment, Harwell, England.

**) The complete lecture has been published in De Ingenieur, 64, O. 51, 1952 (No. 14).

However, because of the success of the cyclotron for accelerating heavy particles, and the betatron for electrons, together with the lack of high powers at microwavelengths, which are essential for convenient configurations of linear accelerators, their development stopped until about 1945. By that time great advances had been made in the development of pulsed ultra high frequency power sources, due to the importance of such sources for radar and similar devices. Mean pulse powers of up to 2 MW's for several microseconds at repetition rates up to 500 pulses per second were available in the frequency range 150-3000 Mc/s. These high peak powers together with their associated new circuit techniques offered the possibility of the linear accelerator comparing favourably on technical and economic grounds with other methods of particle acceleration. The design of microwave linear accelerators using high powers and new techniques was started in several different laboratories.

Principle of travelling wave accelerator

The basic aim of all forms of linear accelerators is to establish suitably phased components of electric field along an axis down which the particles are to be accelerated, in such a way that the particle energy steadily increases. This will take place if the phase velocity of a progressive electromagnetic wave with a component of electric field in the direction of wave propagation can be controlled in a way which keeps the wave in phase with the particles being accelerated.

It may be seen that acceleration is possible in this way by reference to *fig. 1*. Let this represent the local variation, at any given instant in time, of the axial electric field of a wave progressing from left to right, with peak field E. A charged particle at B (or D) is subject momentarily to the accelerating field E_m. If the particle at that instant moves to the right with a velocity much less (or greater) than that of the wave, it will continuously shift its position relative to the field distribution indicated, the force to which it is subject will rapidly change from accelerating to decelerating and vice versa, so that the mean energy imparted to the particle by the wave will be zero. If, however, the particle velocity at that instant is equal to the phase velocity of the wave, the particle will retain its relative position in the wave and it will be subject to the constant accelerating field $E_m = E \sin \Theta_s$, as represented by the dotted horizontal line, Θ_s being the phase of the particle relative to point O (zero field) in fig. 1. As the particle velocity will increase due to the accelerating force, its position in the wave can be maintained only if the phase velocity of the wave is made to increase likewise and at the same rate. The energy gained by a particle of charge e, after travelling a distance z in the constant accelerating field E_m, is $ezE \sin \Theta_s$. Denoting the total energy (rest and kinetic) of the particle by ϵ and its rest mass by m_0, its velocity v_p is given by the relativistic formula:

$$\epsilon = \frac{m_0c^2}{\sqrt{1-\left(\frac{v_p}{c}\right)^2}} = ezE\sin\Theta_s + \text{const.} \qquad (1)$$

(c being the velocity of light). Hence, this is the required dependence of the phase velocity $v = v_p$ of the wave on the distance z along the axis.

Under this condition, particles displaced from B (or D) find themselves in a field which produces either too much acceleration or too little, thus restoring them to the phase stable point B, around which the particles will oscillate. Likewise

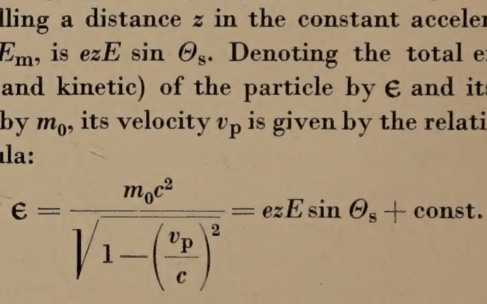

Fig. 1. Instantaneous values of electric field in z-direction, of wave travelling in this direction. The phase velocity of the wave increases in z-direction in such a way as to maintain a particle at B (or D etc.) in a constant accelerating field (E_m). Particles at B or D are in stable equilibrium, at A or C in unstable equilibrium.

particles at A (or C) are in unstable equilibrium. Mathematical analyses of the motion of particles trapped in a wave in this way have been carried out 7) 8) and have shown there is damping of the amplitude of these phase oscillations with increasing energy both for slow and relativistic speeds and that generally the phase oscillations have a frequency much lower than that of the wave, almost ceasing to exist in the relativistic region. If particles are injected continuously into the wave with a velocity close to its initial phase velocity only those in the region from A to, say, P will be trapped in resonance with it and become bunched around B. Those starting with too large an initial displacement, i.e. from P to C in advance of the stable phase, will fall back beyond A and be lost.

The value of the phase Θ_s of the position of stable equilibrium and, hence, the mean accelerating field acting on the particles oscillating around this position may be influenced by a suitable choice of the local variation of the phase velocity of the wave. With increasing mean accelerating field the trapping region decreases and it ceases to exist when this field equals the peak field. In the initial stages of an accelerator in order to trap a large number of particles it is advisable for the position of stable equilibrium to be well in advance of the wave crest. After trapping and bunching has been accomplished the equilibrium position, again by altering the phase velocity of the wave, may be moved nearer to the wave crest to obtain an increased rate of acceleration.

This description has ignored any radial motion of the particle. However, several workers 7)9) have shown using Maxwell's electromagnetic field equations for an axially symmetrical travelling wave, that in general there must be radial forces as well as an axial force acting upon the particles. In the region where phase stability exists the net radial force is defocusing, although as the particle velocity becomes close to the velocity of light the radial focusing force due to the circular component of the magnetic field becomes almost equal to the defocusing force due to the radial component of the electric field and the defocusing is only slight. Fortunately, radial stability may be restored by the application of a paraxial magnetic field of strength proportional to $1/\sqrt{V}$ where V is the kinetic energy of the particle.

The corrugated waveguide

To accelerate particles in this way it was necessary to produce a progressive wave with an axial component of electric field and a phase velocity equal to the particle velocity and therefore less than the velocity of light.

No well recognised method for producing a guided wave with these particular characteristics existed in 1945, although guided waves with a longitudinal component of electric field and a phase velocity greater than the velocity of light were well known by workers in the microwave field as one of many possible modes of wave propagation in a waveguide.

That waves may be propagated with other electric and magnetic field configurations than those which are set up on a two wire transmission line, i.e. the electric and magnetic field components mutually at right angles to each other and to the direction of propagation, may be illustrated by reference to a rectangular waveguide. This may be considered to be made up of two strips AB forming a twin wire transmission line continuously stub supported along both of its edges (*fig. 2a*). Such a stub loaded transmission line may be represented by the equivalent circuit shown in fig. 2*b*, which may be regarded as a highpass filter whose cut-off frequency is the resonant frequency of the parallel tuned circuits, i.e. the frequency at which the stubs are $\lambda/4$ long. When the stubs occur very closely spaced, together they

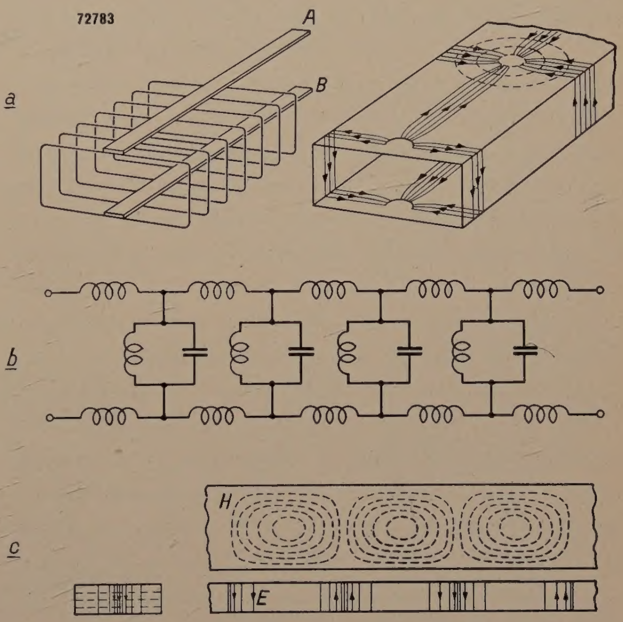

Fig. 2. *a*) A rectangular waveguide propagating a H_{01} wave, with currents flowing in the walls as shown in the righthand picture, may be considered to be made up of a continuously stub supported twin wire transmission line AB (lefthand picture).
b) Equivalent circuit of this transmission line.
c) Pattern of electric field E (full lines) and magnetic field H (dotted lines) in the rectangular waveguide (*a*). The electric field has no component in the direction of wave propagation.

form what is substantially a rectangular tube and the currents flowing in the transmission lines correspond to the currents in the top and bottom walls of a rectangular waveguide. These longitudinal currents fall to zero at the edges of the walls and there are no longitudinal currents in the side walls. The currents flowing in the stubs correspond to the transverse currents set up in the side walls when a H_{01} wave travels down the rectangular tube *). The electric and magnetic field patterns which are set up within the guide due to these currents flowing in the walls are shown in fig. 2*c*. The electric component of the field (full lines) is normal to the wide faces of the guide and at right angles to the direction of wave propagation, while there are both longitudinal and transverse components of the magnetic field (broken lines). This mode of propagation is of no interest for particle acceleration, since it has no axial component of electric field. However, there are others, the E modes, which are of interest.

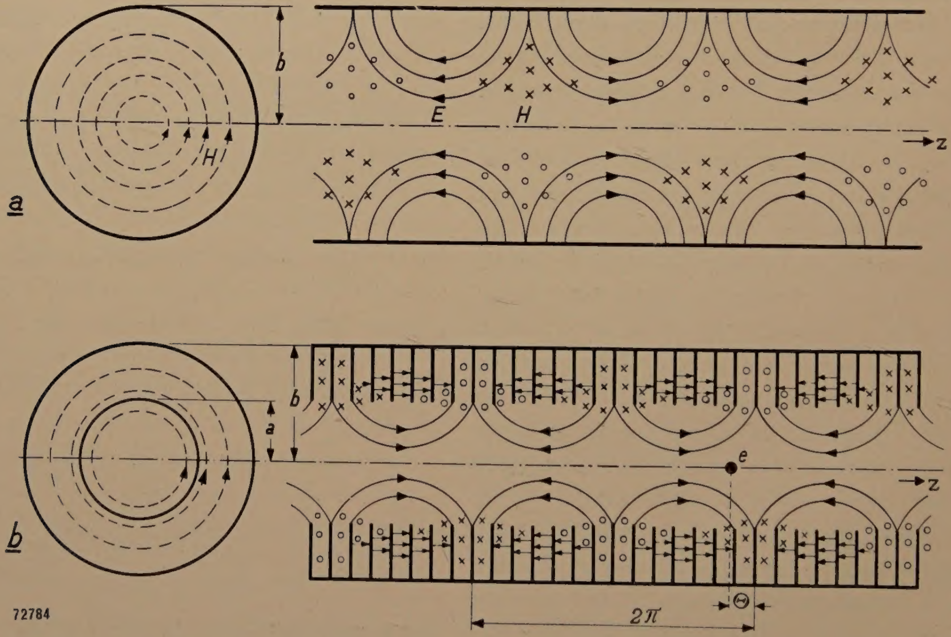

Fig. 3. *a*) Field pattern of E_{01} wave in circular waveguide of diameter *b*. Full lines electric field. The lines of magnetic force are circles around the axis.
b) Field pattern of E_{01} wave in corrugated circular waveguide. *e* = typical position of particle experiencing acceleration.

Stratton[10]) for instance shows that in a smooth-walled guide of circular cross-section electromagnetic waves having the field patterns shown in *fig. 3a* may be propagated if their frequency (in c/s) is greater than 0.38 *c*/*b*, where *c* is the velocity of light in cm/s and *b* the tube radius in cm. This is the cut-off frequency for the tube, which behaves like a conventional highpass filter. The phase velocity of these waves when propagated in a smooth-walled cylindrical tube may be shown to be greater than the velocity of light. To make them suitable for accelerating particles a means of controlling their phase velocity and reducing it to be less instead of greater than *c* has to be found. Several methods were proposed. The one which was adopted in the A.E.R.E. Laboratory and in the Microwave Laboratory of Stanford University uses metal irises, shown diagrammatically in fig. 3*b*. These irises form deep corrugations protruding from the wall of the cylindrical guide. For close spacings each corrugation may be regarded as a radial parallel plate transmission line. When their depth is less than a quarter of a wave they provide an inductive loading in the guide wall and by analogy with an inductively loaded transmission line it is to be expected that the velocity of propagation of the waves passing along the tube will be decreased.

A careful study of the equations governing the field existing within such a structure was first made by Cutler[11]), who obtained solutions of them which were satisfactory for many purposes by assuming that the corrugations were thin and closely spaced compared with a wavelength. These solutions confirmed that wave propagation in such a structure could take place and that *by suitable control of the corrugation depth the phase velocity* v_p *for a given frequency could be made equal to or less than the velocity of light;* in fact, a specific value could, within limits, be obtained at any given point of the guide. They also showed that the fields exhibit some rather special characteristics when $v_p = c$. In particular the accelerating field is uniform over the open part of the tube and (in Giorgi units) is at any cross-section given by

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*) Readers may refer to the articles by W. Opechowski, Philips techn. Rev. **10**, 13-25 and 46-54, 1948, which contain a somewhat more elaborate discussion of waves in waveguides of different shapes. *Ed.*

$$E = (480\,W)^{\frac{1}{2}}\,(\lambda/\pi a^2)\,, \quad . \; . \; . \; . \quad (2)$$

where W is the power flowing through the cross section, a is the radius of the iris aperture and λ the wavelength. For the same input power to guides of different radii the accelerating field is inversely proportional to the square of the inner radii, and as the inner radius decreases the fields inside the corrugations tend to those in a cavity resonator supporting an E_{010} mode.

As the power travels along the guide it is attenuated by copper loss in the plane dividing walls of the corrugations. The number of irises should therefore be made as few as possible without seriously reducing the efficiency of the guide for accelerating particles. Walkinshaw [12]) has shown that for a travelling wave accelerator the best performance is obtained when there are 3-4 corrugations per wavelength. With a larger number the copper loss is unnecessarily high, with fewer, i.e. as the corrugation spacing increases, the accelerating field for a given power flux decreases. This decrease occurs because the field between corrugations becomes less uniform so that higher harmonic components of the wave are set up. These carry a proportion of the power which is no longer available for acceleration.

With two corrugations per guide wavelength the travelling wave form of accelerator is no longer possible. The irises occur at half wavelength spacings and each corrugation is then in resonance with the frequency of the radio frequency power being fed into it. A standing wave instead of a travelling wave pattern builds up in the guide and it becomes a multiple resonator with a phase change of 180° between successive corrugations. This is the π -mode of resonance often used in magnetrons. When the periodic structure is resonant it is no longer possible to transmit power through it.

A resonant structure such as this with a standing wave field pattern set up in it provides an alternative form of linear accelerator, for the standing wave pattern may be regarded as being made up of two travelling waves moving in opposite directions. Particles injected into such a field with a velocity equal to that of one of the component waves would experience similar forces acting upon them to particles in a travelling wave accelerator for the effect of the reverse wave upon them must on a time average be zero. It has been claimed [7]) that the standing wave method has an important technical advantage over the travelling wave method despite the wastage of power in the reverse wave. This is its ability to act as the frequency stabilising cavity for the radio frequency oscillator driving it. However, this has never yet been demonstrated experimentally to be an important advantage.

Use of corrugated waveguide for travelling wave accelerator

Several papers have now been published [8]) [9]) [13]) on the properties of corrugated guides suitable for travelling wave accelerators. They give theoretical data of the axial fields obtainable in metal corrugated guides when the phase velocity is made equal to c for different iris apertures and taking into account attenuation of power in the guide. Actually particles are injected into the waveguide at a velocity much less than c: in fact for electrons an initial velocity of about 0.4 c is chosen, but after "surf-riding" on the wave over only a short distance, velocities very near c are attained, further acceleration virtually causes only an increase in mass of the electron (at 2 MeV energy, the electron velocity is already about 0.98 c).

Because of the attenuation of the power, the accelerating field E according to formula (2) decreases along the guide. The total energy of a particle at the end of the guide is given by the integral of E over the given length (cf. form. 1). Harvie [9]) has published graphs showing the integrated field (particle energy) in a series of guides of differing inner radii fed with 2 MW's peak power on a wavelength of 10 cm for guides with 10 corrugations per wavelength. This is shown in *fig. 4a.* The independent parameter is the inner radius expressed as a/λ where λ is the free space wavelength of the radio frequency power being fed into the waveguide. The envelope of the family of curves, the top chain line, shows the maximum attainable energy (i.e., assuming the particles to travel at $\Theta_s = 90°$) for any given length of accelerating tube, each length corresponding to a definite value of a/λ. The limitation imposed on each curve where it flattens off is entirely due to attenuation. However, other more serious limitations to the maximum energy attainable in an accelerator may often be present, such as those imposed by frequency and temperature variations and also by dimensional errors arising in manufacture.

The importance of the frequency stability of the radio frequency source is to be seen from the remaining dotted curves in this figure. They show the limit of energy attainable with a guide of given a/λ when it is assumed that the maximum permissible phase error of the particles in the wave is

$2\pi/10$ radians. In an ideal accelerator the wave and particles would remain in step along the whole length of the accelerator irrespective of the radio frequency. In a corrugated waveguide this does not happen because the energy stored in the corrugations is a rapidly varying function of frequency which gives it the characteristics of a highly dispersive medium. If the waveguide is designed to have the correct phase velocity at a given frequency, then at any other frequency the particles being accelerated will no longer be in the correct phase relationship with the wave. It may be seen that frequency variations of a few parts in 10^4, i.e. about the best stability that can be obtained in practical cases, impose severe limitations on the permissible length of guide.

A similar effect is to be expected due to temperature variations of the waveguide. For the coefficient of expansion of copper is about 1.65×10^{-5}, thus a change of 1 °C in guide temperature (changing the radius b) corresponds to a $d\lambda/\lambda = 1.65\times10^{-5}$; or a temperature variation of ±10 °C is equivalent to a wavelength tolerance curve of $d\lambda/\lambda = 1.65\times 10^{-4}$. The effects of temperature variations are easier to overcome than frequency changes for they occur more slowly and may be compensated by small changes in the operating frequency. Nonetheless, the figures are sufficient to show that the waveguide dimensions must be determined with a high degree of precision. In fact with an intolerably high degree for long accelerators. Fortunately it is possible to construct a long guide of a number of sections joined together by short sections which may be used for phase correction. In practice it has been found that a guide 2 metres long with $a/\lambda = 0.2$ and ten corrugations per wavelength may be constructed to have a phase error within approx. 18° of that predicted by theory. For a guide with this value of inner radius this seems to be approximately the right section length.

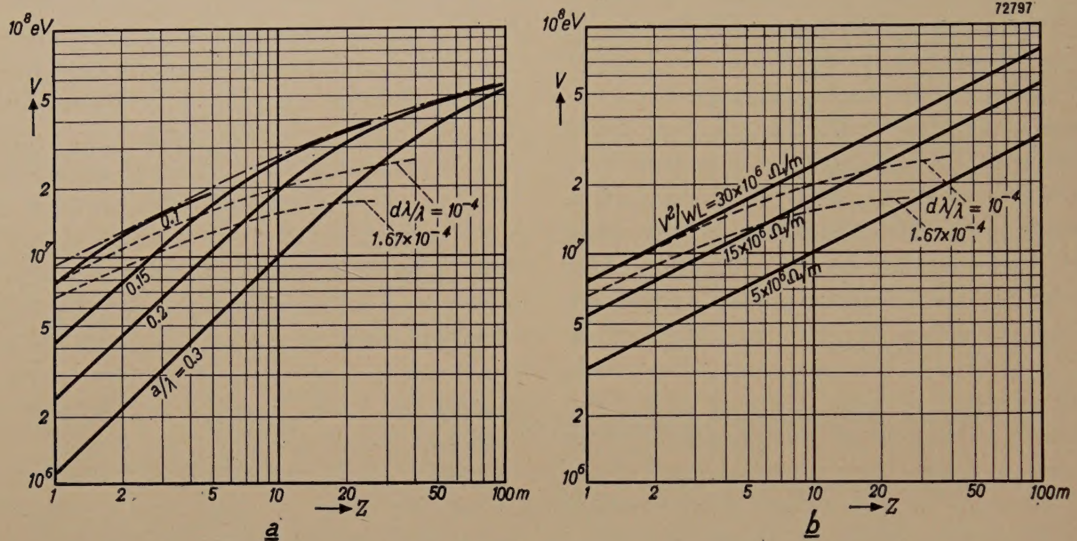

Fig. 4. *a*) Maximum particle energy V obtainable in a corrugated waveguide of given length Z, for different inner radii a of the irises. The curves are calculated for a guide containing 10 irises per wavelength, a phase velocity $v_p = c$ (the stable position of the particles — electrons — being located at the wave crest, $\Theta_s = 90°$), wavelength $\lambda = 10$ cm, input power 2×10^6 W. The flattening off of the curves is due to the attenuation of the wave travelling in the guide. The intersection of each full line with one of the broken lines indicates the guide length Z at which with a given frequency stability $d\lambda/\lambda$, the phase error attains the assumed limit of 36°.
b) Constant "efficiency" contours (V^2/WL = const., see below) graphed together with the frequency tolerance curves ($d\lambda/\lambda$ = const.) from (*a*). With a given frequency stability high efficiencies can be obtained by using a short length $Z = L$ and a small a/λ value.

It will be seen in fig. 4*a* that for a given power input the acceleration per unit length increases rapidly and the maximum usable length decreases with decreasing inner radius. When it is required to accelerate particles to a given energy it is relevant to consider whether a long guide of large inner radius or a shorter guide of smaller inner radius should be used.

In deciding this it is convenient to consider the relative waveguide "efficiency" as defined by the ratio

$$\frac{(\text{energy})^2}{\text{peak input power} \times \text{guide length}} = \frac{V^2}{WL}\,\frac{\text{megohms}}{\text{metre}},$$

when V is in MeV, W in megawatts and L in metres.

Since this is a function both of power and length it is an indication of economy. Also it is almost the same as the effective series impedance of a unit length of accelerator and so may be used to make a rapid assessment of the characteristics of any high energy accelerator, which may be considered to be made up of a number of component accelerators. Constant "efficiency" contours may also be graphed together with the frequency tolerance curves as has been done in fig. 4*b*. These contours are straight lines of equal slopes, with the "efficiency" proportional to the square of the intercept on the ordinate. They are cut by the frequency tolerance curves in a similar way to that in which the a/λ curves are cut in fig. 4*a*. It may be seen from figs. 4*a* and *b* that for high "efficiencies" it is necessary to use small a/λ 's and short lengths.

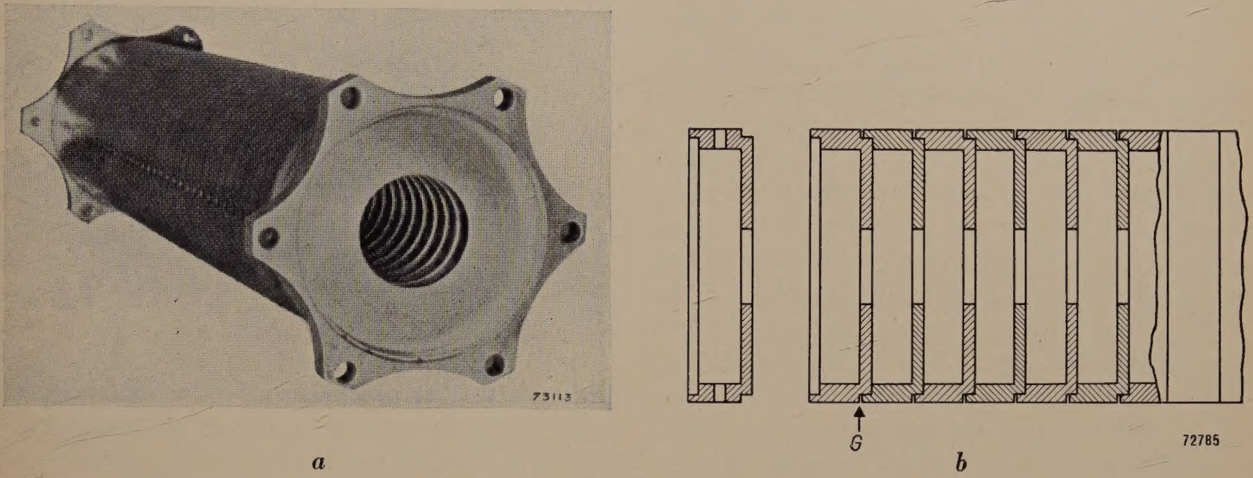

Fig. 5. *a*) 40 cm section of corrugated circular waveguide, made at A.E.R.E.
b) Construction of the guide shown in (*a*). To the left a single machined element, to the right several assembled elements (partly sectionalised). The push fitting elements are clamped together and the 0.010″ gap *G* is filled with soft solder.

Waveguide construction and performance

Mullett and **Loach** [14]) have described in detail the methods of feeding, and measured characteristics of corrugated guides made at A.E.R.E. *Fig. 5a* shows a photograph of a section 40 cms long with an $a/\lambda = 0.2$ and 10 corrugations per wavelength, and its method of construction is shown in fig. 5*b*. Each corrugated element was machined from pure H.C. copper and made self locating with its adjacent elements by spigots. Gaps of 0.010″ were left on the outside of the guide between elements, which were later filled with soft solder to provide some mechanical strength, but the obtaining of good conductivity across the joint at the bottom of the corrugations relied upon pressure contact. The power attenuation measured in guides made in this way was approximately twice the theoretical value for pure copper. Later guides made for a 10 MeV accelerator using a silver soldering method have had considerably greater mechanical strength than the A.E.R.E. ones and the copper loss was only approximately 25% greater than that predicted by theory.

To investigate the accuracy of the theory relating phase velocity with the various guide parameters such as inner radius, depth of corrugation, pitch of corrugation, etc. a number of guides were made up in which these parameters had been suitably varied.

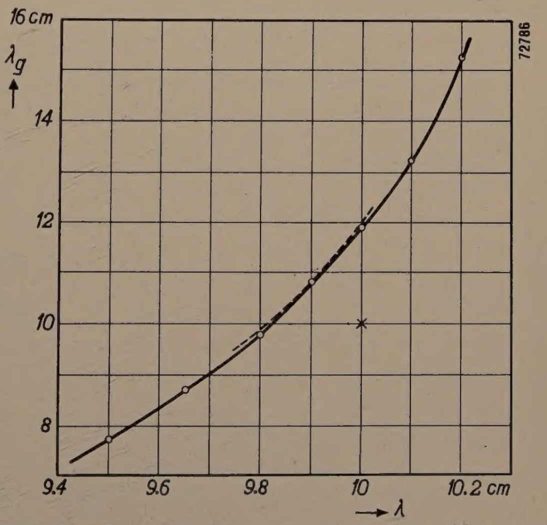

Fig. 6. Wavelength λ_g in corrugated circular guides as a function of frequency (wavelength λ in free space). The dots indicate values measured for guides with 2 cm pitch, $a/\lambda = 0.2$ and outer iris radius *b* calculated on the elementary theory to give $\lambda_g = 10$ cm for $\lambda = 10$ cm (×). The dotted line is calculated from a more refined theory by Walkinshaw [8]).

The phase velocity in each guide was measured as a function of frequency by shorting it at one end, feeding power into it, and measuring the standing wave pattern set up in accordance with the relationship $v_p = c\lambda_{\text{guide}}/\lambda_{\text{air}}$. A typical measurement of λ_{guide} versus λ_{air} is shown in *fig. 6* together with the agreement obtained with the approximate theory, and also a more refined one by Walkinshaw [8]) which took account of the field distribution at the mouth of the corrugations.

Two methods were developed for feeding both the radio frequency power and the particles into cylindrical corrugated guides. The first used a tapered coaxial line of suitable dimensions for the magnetic field component in it and in the first cavity of the corrugated guide to be impedance matched. The second method, described as a door-knob feed, was developed by Mullett. It is shown diagrammatically in *fig. 7*. This design is empirical, but it has considerable advantages over the first method both as regards compactness and ease with which it is matched into the waveguide.

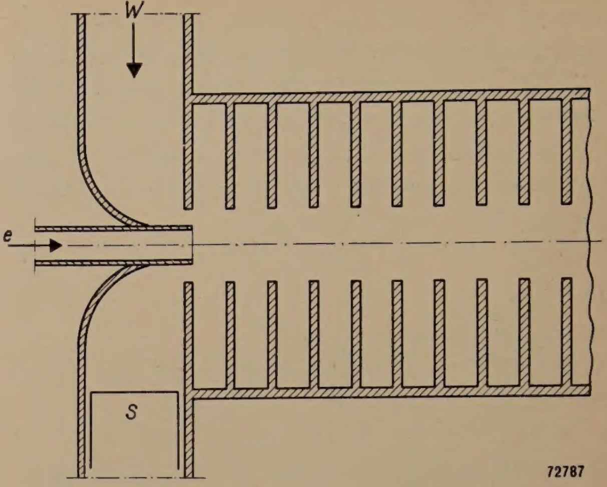

Fig. 7. "Door-knob" feed for the corrugated waveguide. The radio frequency power *W* is fed through a rectangular waveguide 3″ × 1½″, the opposite section of rectangular guide closed by an adjustable piston *S* enabling the exact matching of impedances. Particles (electrons) are injected from *e*.

In the above, the principle of the travelling wave linear accelerator and its mode of operation were outlined with consistent reference to "particles" in general. It must now be stated that considerable practical difficulties are encountered in applying

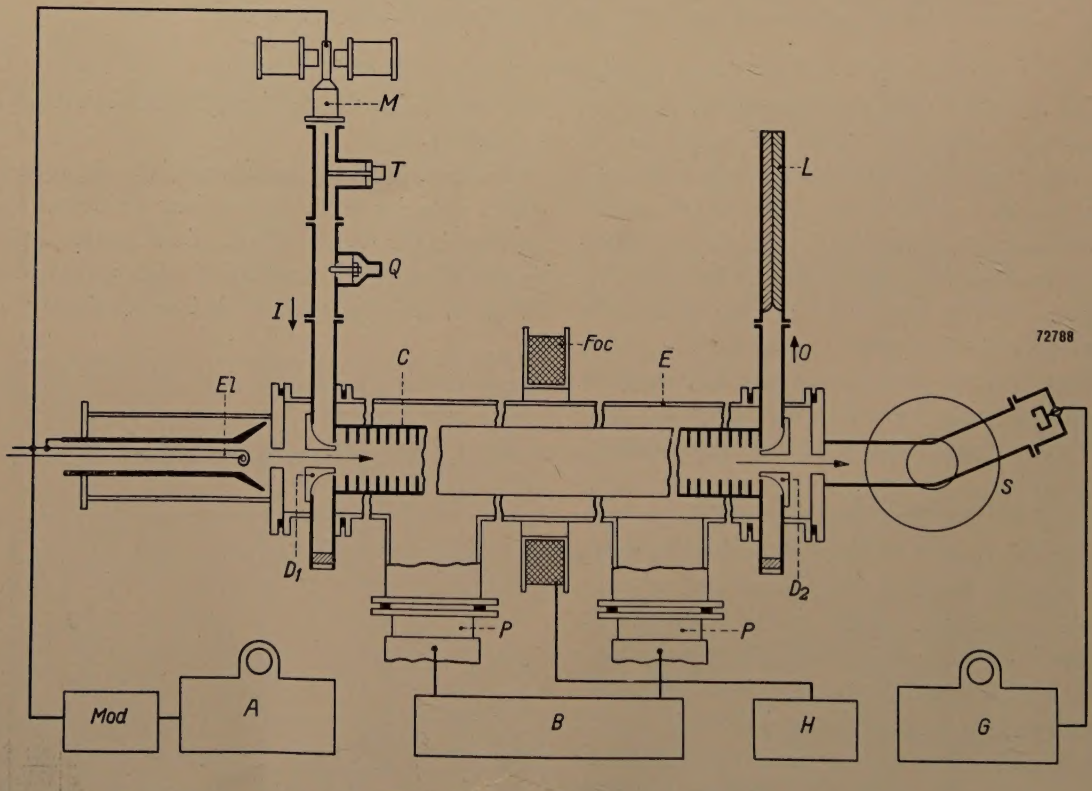

Fig. 8. Block schematic diagram of the 3.5 MeV linear electron accelerator built at A.E.R.E. *C* tapered corrugated waveguide in vacuum envelope *E*, *El* electron gun, *I* radio frequency input, D_1 door-knob feed, D_2 door-knob exit, *O* radio frequency output, *L* steel load taking up remainder of wave power; *M* magnetron with modulator *Mod*; *T* and *Q* line lengthener and probe for adjusting the magnetron operating frequency, *A* synchronising, pulse monitoring, safety interlock, remote control; *Foc* one of 15 focusing coils, *H* focusing current controls; *P* oil diffusion pumps, *B* mechanical rotary backing pump, vacuum pressure monitoring equipment and automatic control; *S* electron spectrometer with deflection coils and Faraday chamber, *G* spectrum analyser control and display unit.

the principle to heavy particle acceleration, so that the remaining part of the article in which a specific machine is to be described only deals with the acceleration of electrons.

The A.E.R.E. 3.5 MeV electron accelerator

The principal characteristics of this accelerator have been described by Fry et al. 15)*. Fig. 8* is a block schematic diagram of it. It is designed to work with a peak input power of 2 MW's in 2 μsec pulses obtained from a magnetron. The power is fed through a $3'' \times 1\frac{1}{2}''$ rectangular waveguide to the input door-knob feed and then into 2 metres of corrugated guide. Unused power, reaching the end of the corrugated guide again passes via a second door-knob feed into a rectangular waveguide and is absorbed in a dummy load. The accelerating tube is mounted inside a vacuum envelope. This envelope is in turn surrounded by focusing coils to provide the steady axial magnetic field necessary for neutralizing the radial defocusing forces acting on the electron beam as mentioned above. Electrons are injected from a diode gun of the Pierce type *) which is pulsed to 45 kV by the modulator which also drives the magnetron. The electrons are injected with a velocity of $0.4c$ into a wave of the same initial phase velocity. By a slight tapering of the first part of the corrugated wave guide, the phase velocity of the wave is matched to the increasing velocity of the electrons. The equilibrium position for accelerated electrons is at first 45° behind the field zero but in the first 40 cms length, by suitably adapting the tapering of the guide, this position is shifted up 10°, to 55°, to take advantage of a higher accelerating field after the electrons have become well bunched. The residual gas pressure measured by ionisation gauges mounted on the vacuum envelope above the pumping ports is 2×10^{-5} mm Hg under normal running conditions. The electrons arriving at the end of the corrugated guide

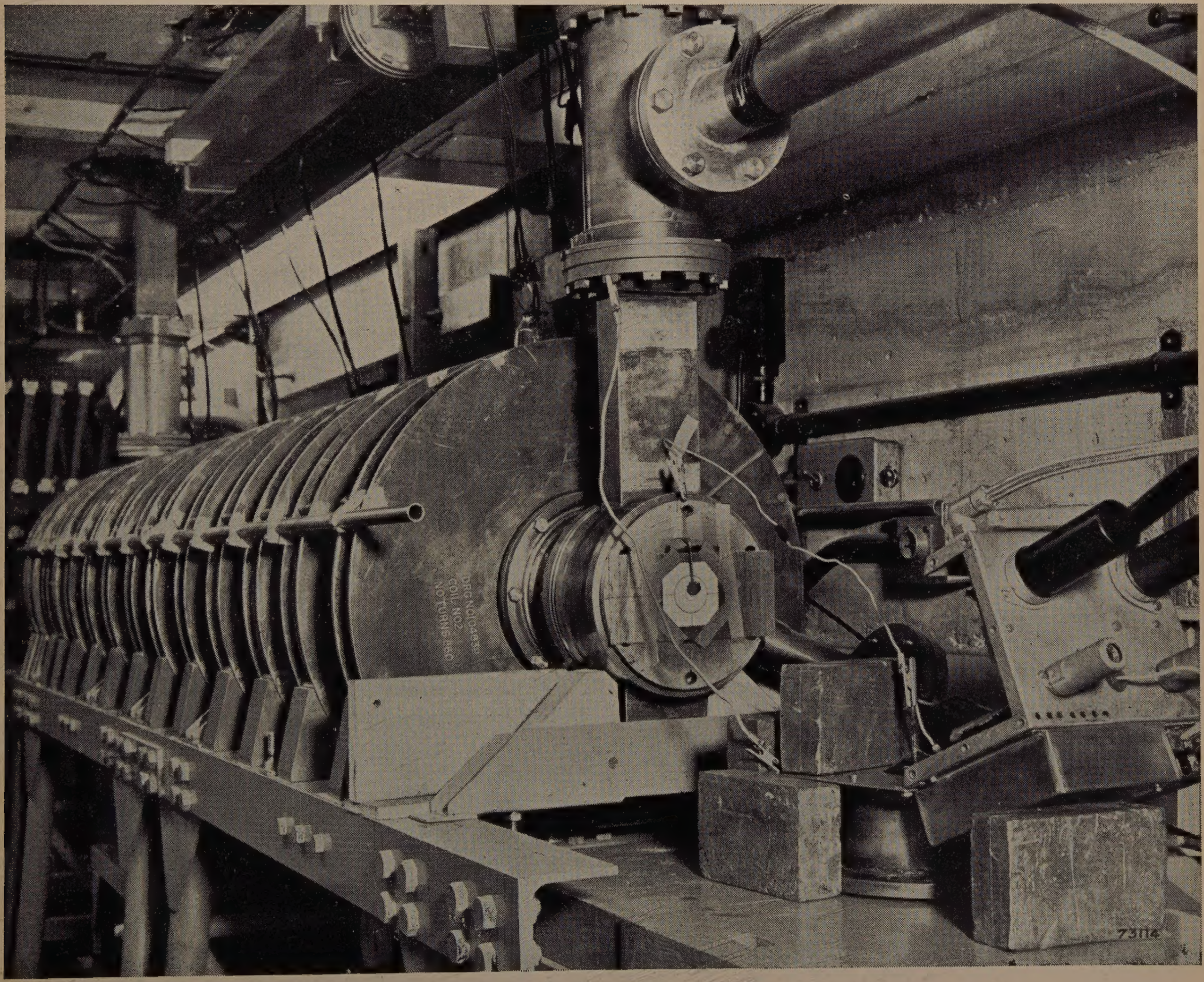

Fig. 9. Photograph of the output end of the 3.5 MeV electron accelerator.

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*) Cf. Philips techn. Rev. **13**, 216, 1951 (No. 8).

are allowed to strike a lead target, their energy being converted into X-rays. A photograph of the output end of the accelerator is shown in *fig. 9.*

This particular guide was designed for no (or very small) beam loading. When a beam of electrons is fed into the guide for acceleration the effective attenuation in the corrugated waveguide increases since appreciable energy is now being transferred to the electrons. Hence, except at the input end, the radio frequency power flow and consequently the field diminish with increasing beam loading. This effect is partially compensated in the bunching region by the electrons tending to move closer to the peak of the wave, i.e. into a region of higher field. Over the main portion of the accelerator, however, the electrons remain at a constant phase with respect to the wave with the net result that the electron energy attained decreases with increasing gun filament (or emission) current.

Preliminary operating data as a function of the gun filament current were published but later and rather more reliable curves obtained with improved measuring techniques are shown in *fig. 10.* Taken at an operating frequency of 2997.6 Mc/s with a peak input power of 2.1 MW's and a pulse repetition rate of 50 pulses per second the curves show electron energy and mean beam intensity, the mean power in the beam, and the X-ray intensity in roentgens/min measured at a distance of 1 metre from the target. With the operating conditions specified the mean input radio frequency power to the system was 210 watts and the highest mean power measured in the beam 76 watts, i.e. an efficiency of 36%, at a beam energy of 2.6 MeV. The highest mean current measured was 20 μA's, which with the duty cycle of 10 000 : 1 corresponds to a mean current in the pulse of 300 mA. Typical operating conditions for the machine are: energy 3.25 MeV, 10 μA's mean current and an output of 31 röntgens/min at 1 metre at 50 pulses per second, although the repetition rate is often increased up to 250 pulses per second. The energy spectrum when the operating conditions are correctly adjusted is a clean one about the mean energy with a full width at half intensity of approximately 5%.

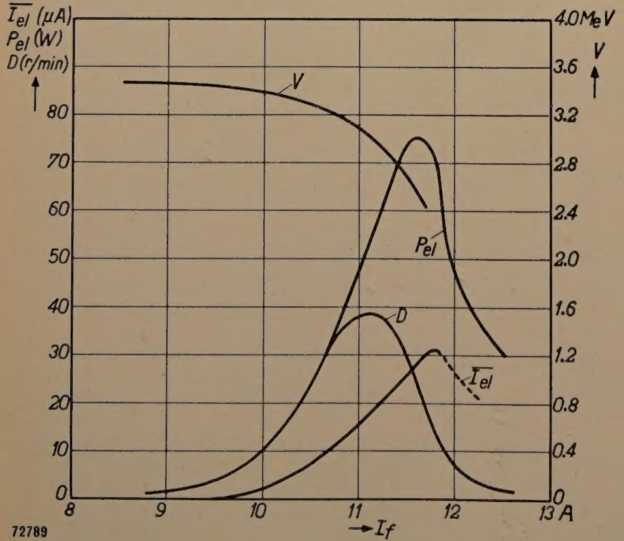

Fig. 10. Operating characteristics of the 3.5 MeV electron accelerator. I_f gun filament current, V energy of the electrons, $\overline{I}_{el}$ mean beam current, P_{el} beam power (dissipated in target), D X-ray dose rate in röntgens/min at 1 metre distance from lead target. Frequency 2997.6 Mc/s, peak input power 2.1 MW, pulse length 2 μsec, repetition rate 50 pulses per second (mean input radio frequency power 210 W).

Linear accelerators with feedback

The discussion of fig. 4 may be summarized in the statement that the most "efficient" corrugated waveguides are those with small a/λ and that the maximum "efficiency" for a guide of a given inner radius occurs when it is long enough for most of the radio frequency power not transferred to the electron beam to be dissipated in the walls with little passing out into the dummy load. These two conditions are also those which demand a very high degree of frequency stability from the radio frequency source if particle acceleration is to be maintained along the whole guide length. The designer of a linear accelerator of the type described may therefore find himself presented with the choice of making a short efficient accelerator which is critical to adjust and operate, or a longer one which is less efficient and correspondingly less critical to set up. This problem is of particular importance when considering the application of the linear accelerator for clinical use. In such an application, the beam intensity must be adequate to allow the treatment times to be kept short even after heavy filtration and collimation of the X-ray beam, while on the other hand the instrument must be engineered in a form which makes the setting up of a patient easy, thus a long and clumsy accelerator would be most undesirable.

A method of improving the "efficiency" of corrugated guides of length short compared with the attenuation length and thus avoiding the need to make the choice described, has been worked out by Harvie and Mullett [16]). It consists of applying radio frequency power feedback in the manner shown diagrammatically in *fig. 11.* The directions of power flow are shown by the arrows, power from the output end of the accelerator being fed back into a suitable bridge circuit where it is combined with the incoming power from the magnetron. It will be noted that the power at the beginning

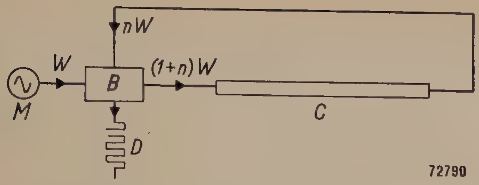

Fig. 11. Schematic diagram of radio frequency feedback circuit. C corrugated guide, B bridge circuit, M magnetron with output power W, D absorbing load (this is necessary only for the build-up period of the power in the guide during every pulse).

of the corrugated waveguide (usually called the circulating power) is then greater than that entering from the magnetron. The novel feature of this system is the radio frequency bridge which is required to have two special characteristics. It must be designed in such a way that all the power is made to flow through the bridge in the proper direction, and the input impedance as seen by the magnetron must be independent of the amount of power fed back from the end of the accelerator. This is necessary in order that the input impedance shall remain constant while the power is building up in the system. The design of such a bridge for the special case when (in the steady state) the power entering the bridge from the feedback arm is equal to the power entering from the radio frequency source has been studied extensively on microwavelengths, the bridges being known as "Magic T's" and "Rat Races" 17). Calculations of the "efficiency" V^2/WL of a fed back accelerator have been made and it is found to increase as the length of the accelerator is decreased from the length for maximum "efficiency" without feedback. The relative "efficiency" in terms of the accelerator length expressed as a fraction of the optimum length is shown in *fig. 12* for the case of no feedback and feedback applied with and without loss in the return path. It may be seen clearly that accelerators short compared with the attenuation limited length may be constructed without loss of "efficiency". This enables increased dimensional tolerances to be permitted on the waveguides and a lower frequency stability from the radio frequency source to be accepted.

Advantage has been taken of this advance in technique in the two different forms of linear accelerator now being developed in Great Britain for clinical use. They are to give 4 and 10 MeV respectively. A number of the lower energy machines are to be built for distribution and use at large medical centres but at present only one is being constructed at the higher energy. Basically both designs are similar to the one described above, but they differ markedly in many of their physical characteristics and particularly in the ways in which they are mounted.

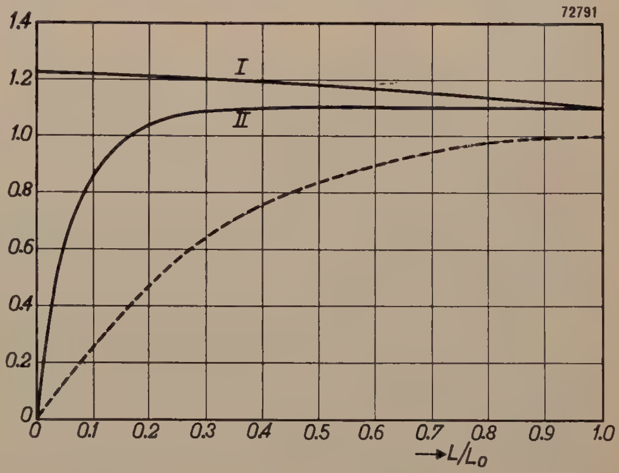

Fig. 12. "Efficiency" V^2/WL of accelerator with feedback (full lines) and without feedback (dotted line) in terms of the accelerator length expressed as a fraction of the optimum length L_0 derived from fig. 4. Curve I: no loss in return path; curve II: loss in return path equal to 5% of that in corrugated guide of length L_0.

Important contributions to the work reviewed in this paper have been made by R. B. R-S-Harvie, L. B. Mullett and W. Walkinshaw of the A.E.R.E. Linear Accelerator Group. Acknowledgement is also made to the Director of the A.E.R.E. for permission to publish this article.

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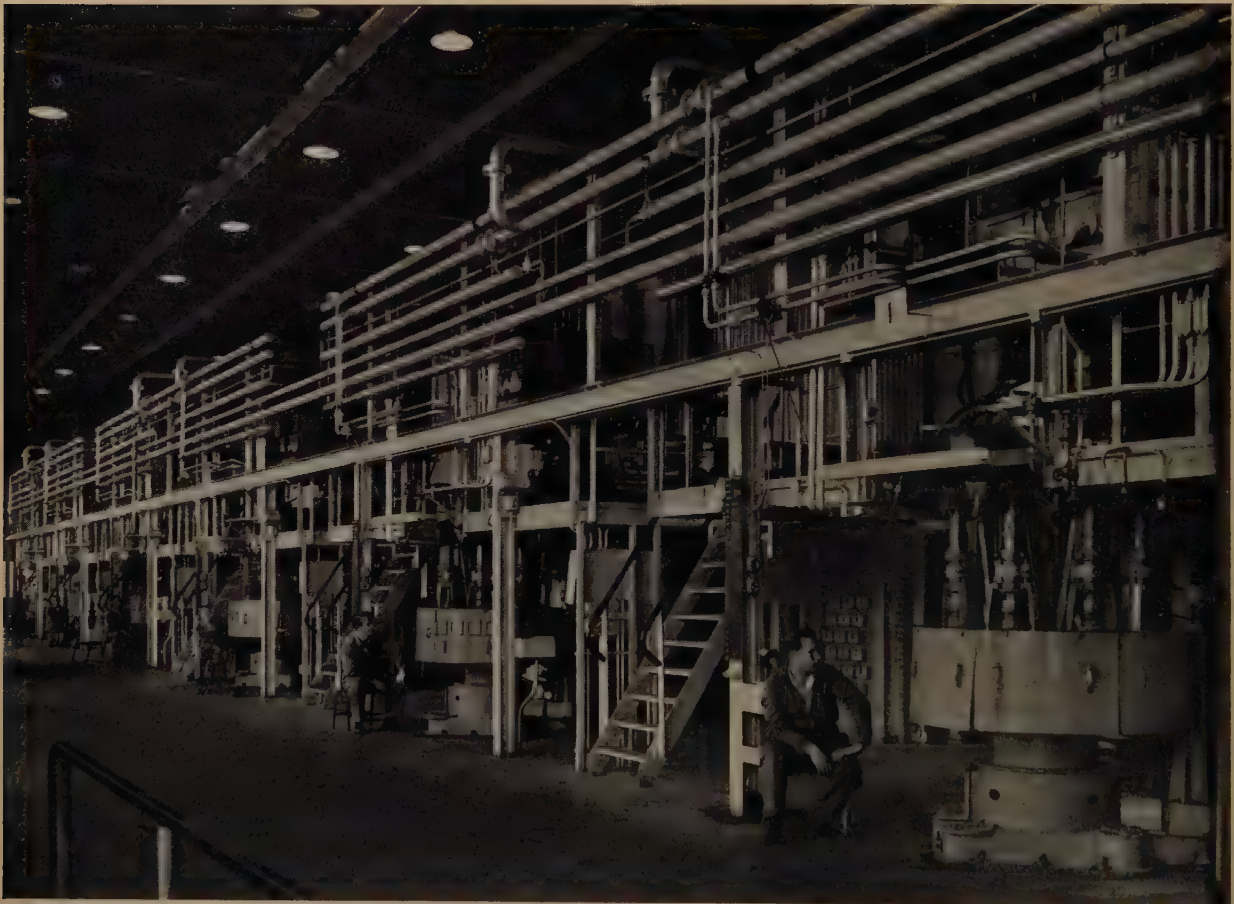
15) D. W. Fry, R. B. R-S-Harvie, L. B. Mullett and W. Walkinshaw, Nature **162**, 859, 1948.
16) R. B. R-S-Harvie and L. B. Mullett, Proc. Phys. Soc. **62B**, 270, 1949.
17) L. D. Smullin and C. G. Montgomery, Microwave Duplexers, McGraw-Hill, New York 1948.

Summary. When particles are injected into an electromagnetic wave of phase velocity equal to the particle velocity and with a component of electric field in the direction of wave propagation, the particles will gain energy from the wave. Electromagnetic waves of the characteristics required may be obtained in a cylindrical waveguide loaded by irises (corrugated waveguide). By a slight tapering of the guide diameter the phase velocity may be controlled in such a way as to keep the waves in step with the particles being accelerated. Under these conditions the particles take up positions of stable equilibrium in the wave and may be accelerated to very high energies, depending on the power of the wave entering the guide, the attenuation of the wave progressing in the guide, and the ratio of inner radius of the corrugations to wavelength. This method of accelerating particles, while known before 1939, became of great interest with the advent of radio frequency sources yielding very large pulse powers on microwavelengths, allowing very high particle energies to be attained with convenient accelerating guide configurations.

In this article the conditions for acceleration are described and some of the fundamental properties of this form of travelling wave particle accelerator outlined. Theoretical and practical limits imposed on the attainable energy are discussed and the "efficiency" is considered. The possibilities of the linear accelerator are illustrated by reference to the characteristics of a 2 metre long electron accelerator now in operation at the Atomic Energy Research Establishment, Harwell, England. In this instrument electrons are accelerated from 45 keV to approximately 3.5 MeV. The operating wavelength is 10 cm. The radio frequency power is obtained from a magnetron in pulses of 2 MW mean value and 2 microseconds pulse length, the maximum pulse recurrence frequency being 250 pulses per second. Mean pulse currents of the beam of accelerated electrons as high as 300 mA have been measured. In machines of more recent design the principle of feedback of the unused radio frequency power has been applied, enabling the acceleration of electrons to high energies in short guides without the inconvenience of too strict frequency stability requirements.

THE PHILIPS BULB BLOWING MACHINE



Glass bulbs form part of the "food" devoured daily in great quantities by incandescent lamp and radio valve factories. They were blown originally, as were so many other glass articles, by means of the human breath, and even up to a few years ago this very old process played its part in the mass production of standardised lamp and valve bulbs ¹).

Nowadays such bulbs are entirely mechanically produced. The photograph shows a number of bulb blowing machines, standing in a bay of the Philips Glass Factory in Eindhoven. Each machine has its own glass furnace, located on the gallery, and fed from the rear with the raw materials for the glass. Below the front portion of each furnace is an opening down through which the glass flows. There is, however, no continuous stream of glass, since immediate-

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¹) See Philips Techn. Rev. 6, 74, 1941.

ly below the opening is a kind of scissors which cuts the stream of glass into portions of a pre-determined weight. Periodically, therefore, a portion of glass falls down and is caught by a continuously rotating turntable, some of which are to be seen in the photograph. The glass is blown on the turntable into a bulb, which is just completed after one revolution of the turntable. The bulb is then ejected and carried by means of a conveyor belt (not visible in the photograph) through an annealing oven to remove strain; via a second conveyor belt, on which it cools, the bulb reaches the inspector who sorts the bulbs according to quality.

The difficulties encountered in developing such an automatic machine lie principally in the achievement of a uniform product, i.e. in keeping constant the weight of the glass portions, this being dependent on many different factors. That these difficulties have been overcome is demonstrated by the fact that the duties of the turntable-man are limited to the occasional adjustment of a tap, checking the weight of a sample bulb, etc.

THE ROLE OF THE ELECTRON MICROSCOPE IN THE INVESTIGATION OF PLANT DISEASES

by E. van SLOGTEREN *). 632.3:581.23:621.385.833

To emphasize the usefulness of the electron microscope in the realm of biology, would be currying coals to Newcastle. Nevertheless, it may well be worth while to consider the role this modern tool of research is playing in a specialized field of biology, phytopathology. The Laboratory for Flowerbulb Research at Lisse, which under the direction of Prof. Dr. E. van Slogteren has for a long time held a prominent place in this field, is one of the institutes availing themselves of the new possibilities offered by electron microscopy. The following invited paper, while providing the readers with a very succinct picture of phytopathological research, will chiefly illustrate the potentialities of the electron microscope by presenting a number of excellent electron micrographs obtained by the workers at Lisse.

Among the numerous varieties of tulips occurring in the standard collections of our florists a number of varieties of the so-called "broken" type are encountered. These are characterized by the petals containing differently coloured parts, which may exhibit various combinations of colours as well as various patterns (flamed, streaked, pinnated, speckled, spotted, etc.). In *fig. 1* a beautiful broken tulip, of the variety Cottage Tulp Perseus, is shown.

These types of tulips are by no means new. The earliest known description of broken tulips was given in 1576 (Clusius). When, in the early seventeenth century, tulips came into vogue, especially in France and in the Netherlands, broken tulips had their share in it. This is testified inter alia by the flower paintings made in those years, as for instance the numerous pictures by the members of the Bosschaert family (father and three sons); one of these pictures is illustrated in *fig. 2.* Broken tulips even were the chief object of the famous tulipomania of the years 1634 to 1637.

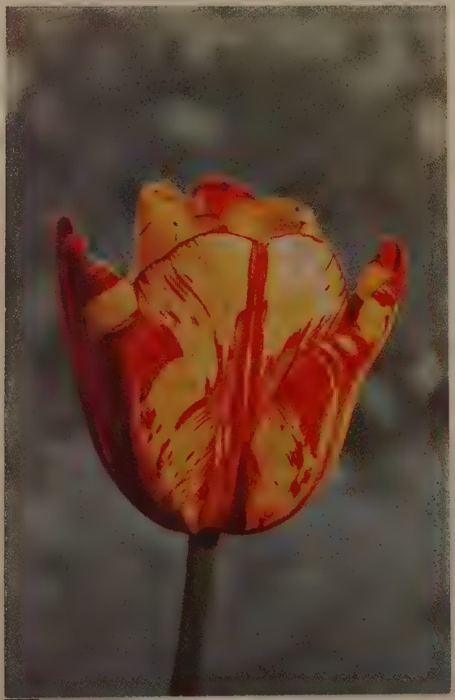

Fig. 1. Broken tulip of the variety Cottage Tulp Perseus. (From: E. van Slogteren and Maria P. de Bruyn Ouboter, Mededelingen Landbouwhogeschool Wageningen **45**, No. 4, 1941.)

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*) Laboratory for Flowerbulb Research, Lisse (Netherlands).

Comparatively new, however, is the knowledge that broken tulips in fact are no varieties of their own, but specimens of common varieties, befallen by a disease, one of whose symptoms is the beautiful spotting or flaming of the petals.

Although in the broken tulip itself the disease apparently does not do much harm and in particular does not seem to affect greatly its reproductive power, the same will in general not apply to other crops (or even other varieties of tulips) to which the disease may be transferred in various ways, e.g. by aphides.

This statement should be amplified. The broken tulip is one of the rare though spectacular cases in which a plant disease may be economically useful. In the vast majority of cases, evidently the contrary is true. In fact, the importance of plant diseases as a virtual threat to human subsistence can scarcely be overestimated. Practically every crop is liable to infection not by one but by a variety of diseases, and the investigation of such diseases may safely be labelled as an objective of major importance of our scientific efforts. Many practical measures have already sprung from such an investigation, ranging from the precautions imposed on the cultivating and marketing of broken tulips to the routine testing of seed-potatoes as to the presence of inter alia the potato X-virus. This test is now compulsory in the Netherlands for all seed-potatoes selected for export.

The potato X-virus: it will be known that many infectious plant diseases may be ascribed to viruses. Viruses are now known to be responsible for the breaking of tulips. Other diseases are caused by fungi, or by bacteria, as e.g. the Yellow disease of hyacinths (caused by Xanthomonas hyacinthi (Wakker) Dowson).

A virus is a parasitical agent found in living tissues and capable of reproduction and of transfer to other tissues. In these respects viruses are similar to bacteria. One of the main characteristics of a virus, however, distinguishing it from bacteria, is its extreme smallness. It was found that virus particles pass through all usual bacterial filters — a fact which in those years when the notion of a virus was only beginning to crystallize [1]) provided a means for concentrating the "agent" and which initially was thought to constitute one of its essential properties. At present some non filter-passing viruses are known, but most viruses are extremely small indeed, too small for observation under the most powerful optical microscope. One of the smallest, the virus of the foot-and-mouth disease, is now known to consist of particles of size about 10 millimicrons.

To-day, more differences existing between viruses and bacteria are known. The most fundamental one is the fact that viruses are capable of reproduction only in living cells, while bacteria form colonies on dead matter, e.g. in broth. This gives evidence that bacteria must be living organisms, whereas for viruses this is still a question open to doubt: by many investigators the opinion is upheld that a virus is not an organism but must be considered simply as a gigantic protein molecule.

By the very smallness of the viruses (from a macroscopic point of view!) frustrating all efforts to make them visible under the microscope, research in this field for many years was curiously handicapped: the effects of the "parasitical agent" could clearly be traced, it could be transferred to other plants, its reaction to chemicals or to other "agents" could be studied — but nobody had ever set eyes on it. Diagnosis, which in the practical fight against plant diseases is all-important, had chiefly to be based on the study of symptoms. In later years it was in some cases greatly aided by the use of a serological reaction, that was developed at (among other laboratories) the Laboratory for Flowerbulb Research at Lisse [2]). This reaction is based on the fact that plant viruses on being brought into animal blood, e.g. of rabbits, provoke the formation of specific antibodies. The serum containing these antibodies (antiserum), when added to a sample of plant juice containing the original virus, will cause an agglutination or precipitation, visible to the eye, of virus particles or plastids that have adsorbed the virus at their surfaces. Only in a limited number of cases, however, antisera could hitherto be obtained, while, on the other hand, even with a positive serological reaction, the diagnosis should not be considered complete as long as, in accordance with one of Robert Koch's postulates, the parasitical agent has not actually been shown in the host.

In these circumstances it is not surprising that, when the electron microscope became of age (and even earlier than that), phytopathologists eagerly seized the possibility offered by this instrument of discerning particles of submicroscopical size, down to 100 mμ or less. As early as in 1939,

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[1]) D. Iwanowski, Ueber die Mosaikkrankheit der Tabakspflanze, Bull. Acad. Imp. Sci. St. Petersb. N.S. III, 35, 67-70, 1892.

[2]) E. van Slogteren, De betekenis van de serologie voor het virusonderzoek, T. Plantenziekten 49, 1-21, 1943 (in Dutch).

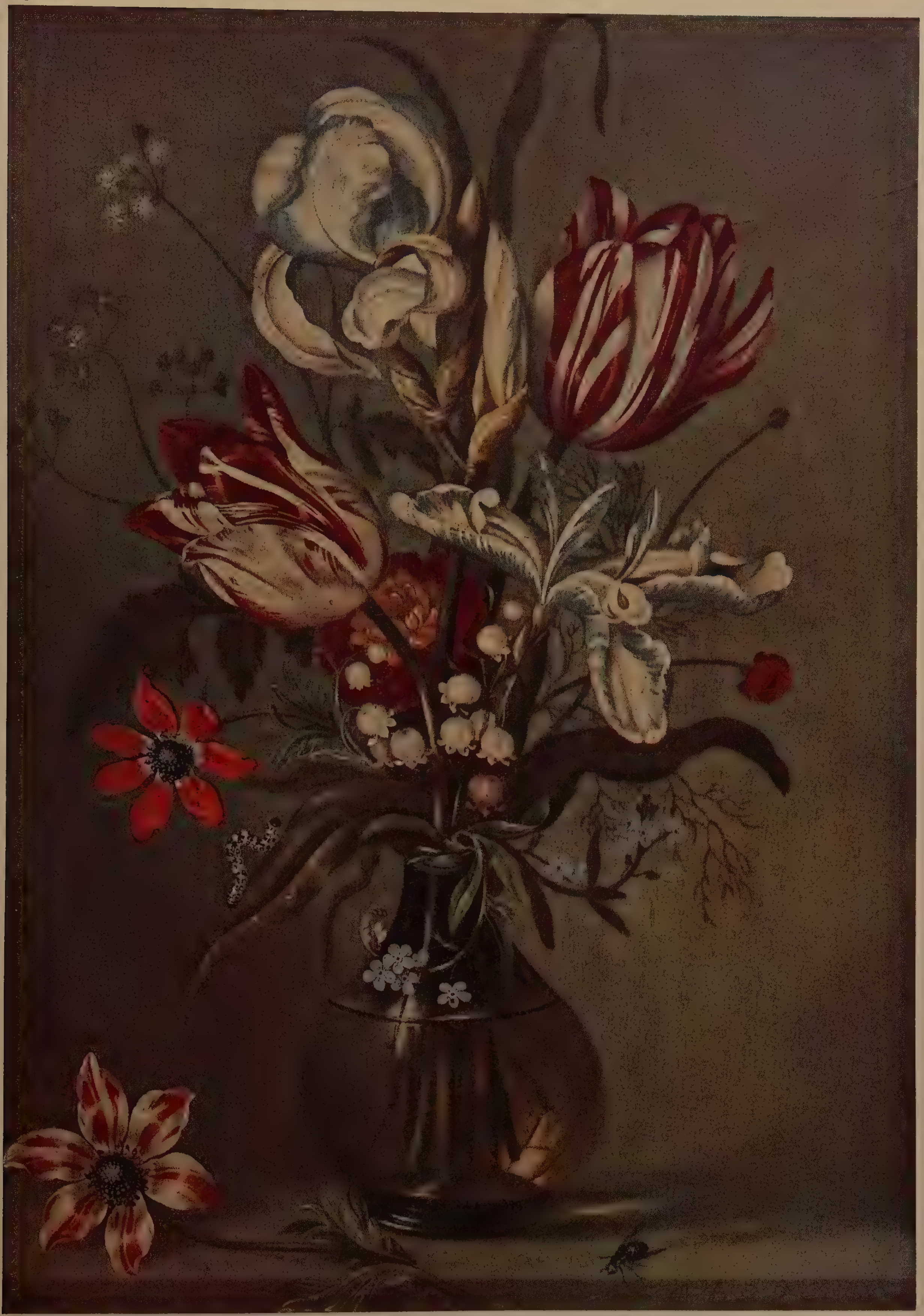

Fig. 2. Painting made by Ambrosius Bosschaert Jr in 1635. Among the flowers two broken tulips are to be seen. (Courtesy of the Director of the Centraal Museum, Utrecht. The reproduction was made by N.V. Wereldbibliotheek, Amsterdam.)

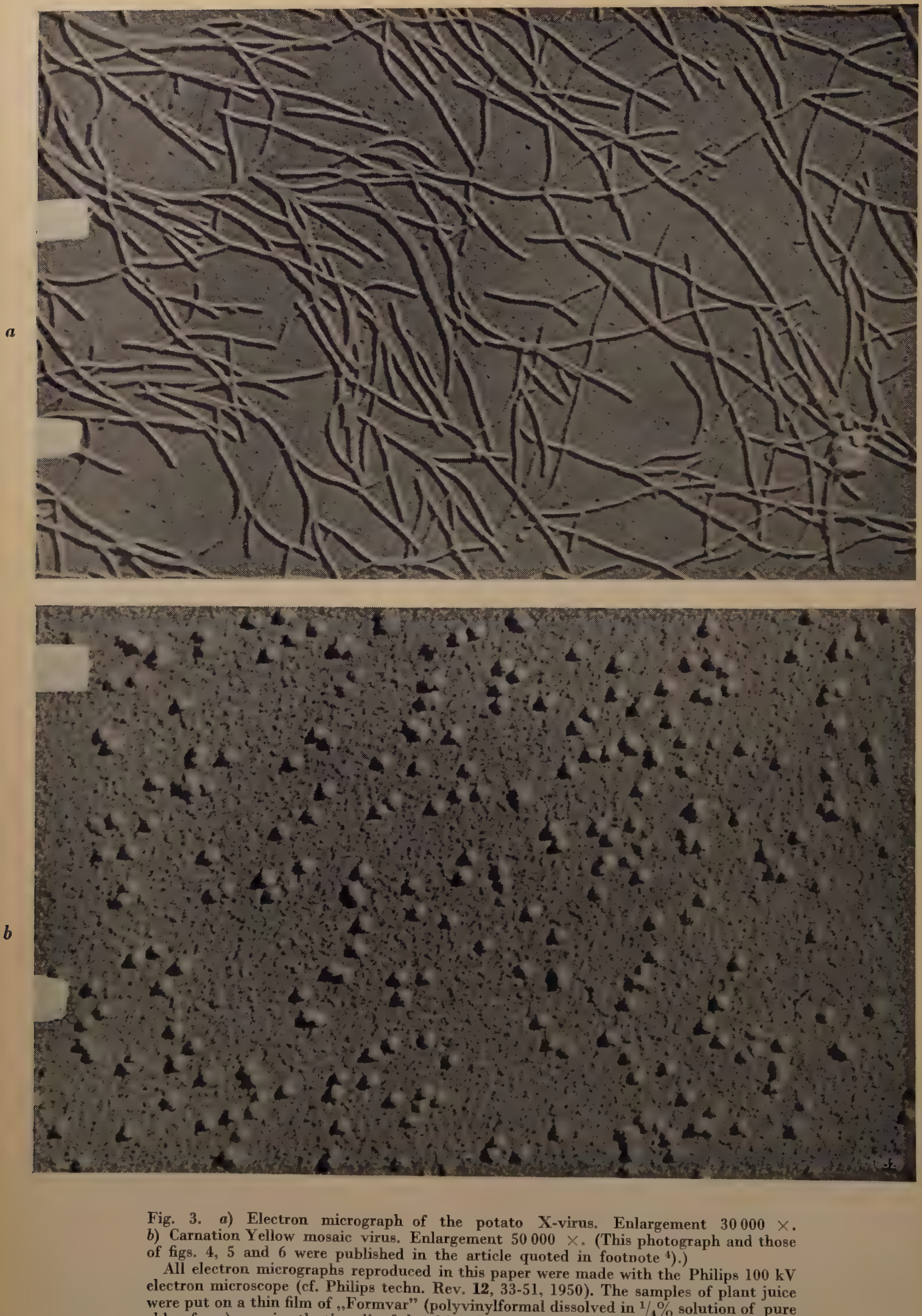

Fig. 3. *a*) Electron micrograph of the potato X-virus. Enlargement 30 000 ×. *b*) Carnation Yellow mosaic virus. Enlargement 50 000 ×. (This photograph and those of figs. 4, 5 and 6 were published in the article quoted in footnote [4]).)

All electron micrographs reproduced in this paper were made with the Philips 100 kV electron microscope (cf. Philips techn. Rev. **12**, 33-51, 1950). The samples of plant juice were put on a thin film of „Formvar" (polyvinylformal dissolved in $^{1}/_{4}\%$ solution of pure chloroform) covering the tiny slit of the object holders. All the samples shown were shadow-cast with palladium. The distance between the blocks at the edge is in all cases 1 μ.

Kausche, Pfankuch and Ruska [3]), using the electron microscope succeeded in rendering plant virus "particles" visible to the eye.

In recent years the electron microscope has been used in many laboratories for the investigation of plant diseases, and it has revealed quite a number of particulars concerning many kinds of viruses. The shape and size of virus particles has been studied (*figs. 3a* and *b*) the character of the serological reaction already mentioned has been investigated, the "crystallization" of some types of virus (e.g. the "bushy stunt" virus of tomato) has been clarified, etc.

Evidently the electron microscope was predestined to assume an important role in diagnostics. By this means, in many cases a contamination could conclusively be proved to be present in suspected plants and the virus involved could be identified [4]). A typical case, encountered in an examination of infected tobacco plants, may be described as follows. Among the different known tobacco diseases, there are two of special importance: tobacco necrosis, associated with a virus consisting of round particles (*fig. 4a*), and the famous tobacco mosaic disease [5]), caused by a rod-shaped virus (*fig. 5a*). Some of the tobacco plants under investigation gave a positive serological reaction with the antiserum of tobacco necrosis and not with the specific tobacco mosaic antiserum; these plants showed in their juice the round virus particles of tobacco necrosis. Other plants reacted positively with tobacco mosaic antiserum and not with tobacco necrosis antiserum; in the juice of these plants the rod-shaped particles of tobacco mosaic virus were found. Still other plants, while not exhibiting the typical symptoms of the disease, reacted positively with both antisera, and indeed an electronmicrograph of their juice revealed the presence of both the round and the rod-shaped virus particles.

The nature of the agglutination observed in these serological reactions is clearly shown by the micrographs fig. 4*b* and 5*b*.

The electron microscope proved quite useful also for recognizing and identifying bacteria causing plant diseases. These relatively large objects can easily be made visible, the only difficulty being to get them in full dress in the picture, with their characteristic cilia (*fig. 6*). When from a preliminary investigation with the ordinary microscope the presence of a specific kind of bacteria is expected, it may well be possible with the electron microscope to identify these bacteria amidst the multitude of ever-present innocuous bacteria, thus saving time by avoiding the necessity of isolating and cultivating the expected bacteria.

Of course, the identification of the agent, especially in the case of a virus disease, will not always be so simple. Too often particles found in the juice of a diseased plant and suspected of being the virus causing the disease are found also in the juice of apparently healthy plants. Thus, if the particles belong to a parasitic agent, it must be an innocuous one, carried by both diseased and healthy plants. In that case some other, undetected, particle may be the cause of the disease. The possibility of the agent proper escaping detection can by no means be ruled out, as in quite a number of cases it has not been possible to find anything even faintly resembling a virus particle in the samples made of the juice of severely diseased plants. The real problem, then, resides in preparing the samples: in the course of the different treatments, such as ultracentrifugation or precipitation with different chemicals, applied to the plant juice in order to enrich its virus content by removing undesired components (plant protoplasm etc.), it may happen that the virus is lost, as for instance it may not easily part with the protoplasm. Moreover, the possibility should not be excluded that the different treatments might change the size and shape of the virus particles or might produce "artefacts" in the picture, which in comparing these particles with other types, known before, obviously may give rise to serious misinterpretations.

To conclude and summarize these remarks it should be stated that the power of the electron microscope can only be put to good use in plant virology when combined with all other methods of approaching the many-sided problems in this field. Experience of different laboratories in the preparation of samples should be exchanged, and no electron micrograph of particles supposed to belong to a new type of virus should be given without a short indication as to how the material has been treated. When such precautions will have eliminated all possible doubt concerning the identity between the original object and the picture obtained, the electron microscope, besides providing a valuable assistance in routine examinations,

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[3]) G. A. Kausche, E. Pfankuch and H. Ruska, Die Sichtbarmachung von pflanzlichem Virus im Übermikroskop, Naturwiss. **27**, 292-299, 1939.

[4]) Maria P. de Bruyn Ouboter, J. J. Beijer and E. van Slogteren, Diagnosis of plant diseases by electron microscopy, Antonie van Leeuwenhoek **17**, 189-208, March 1951.

[5]) Cf. footnote [1]) and a great number of papers published by W. M. Stanley in the years between 1930 and 1940 in Science, J. biol. Chem. and other journals.

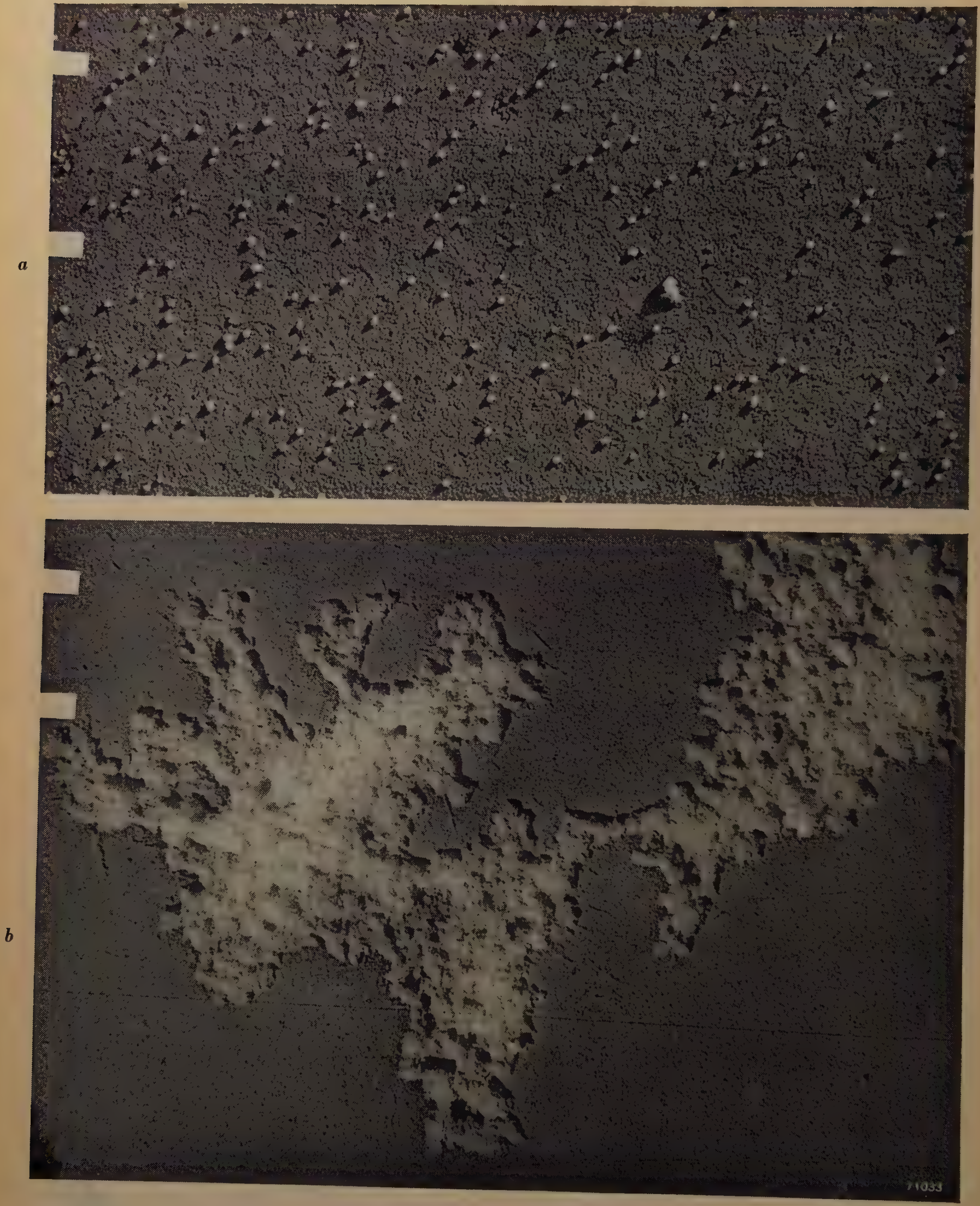

Fig. 4. *a*) Tobacco necrosis virus, obtained from tobacco plants (this virus is also known as causing the Augusta-ziek of tulips). Enlargement 28 000 ×. As an example, the complete procedure of purification is indicated in this case: the foliages were minced, frozen for a night, squeezed, the juice centrifuged for 30 minutes at 3500 rev/min, purified with ammonium sulphate, centrifuged for 30 min at 3500 rev/min, 5× concentrated by centrifuging for 40 min at 40 000 rev/min, and dialysed one night.
b) Same virus as (*a*), showing positive serological reaction with tobacco necrosis antiserum. Enlargement 18 000 ×.

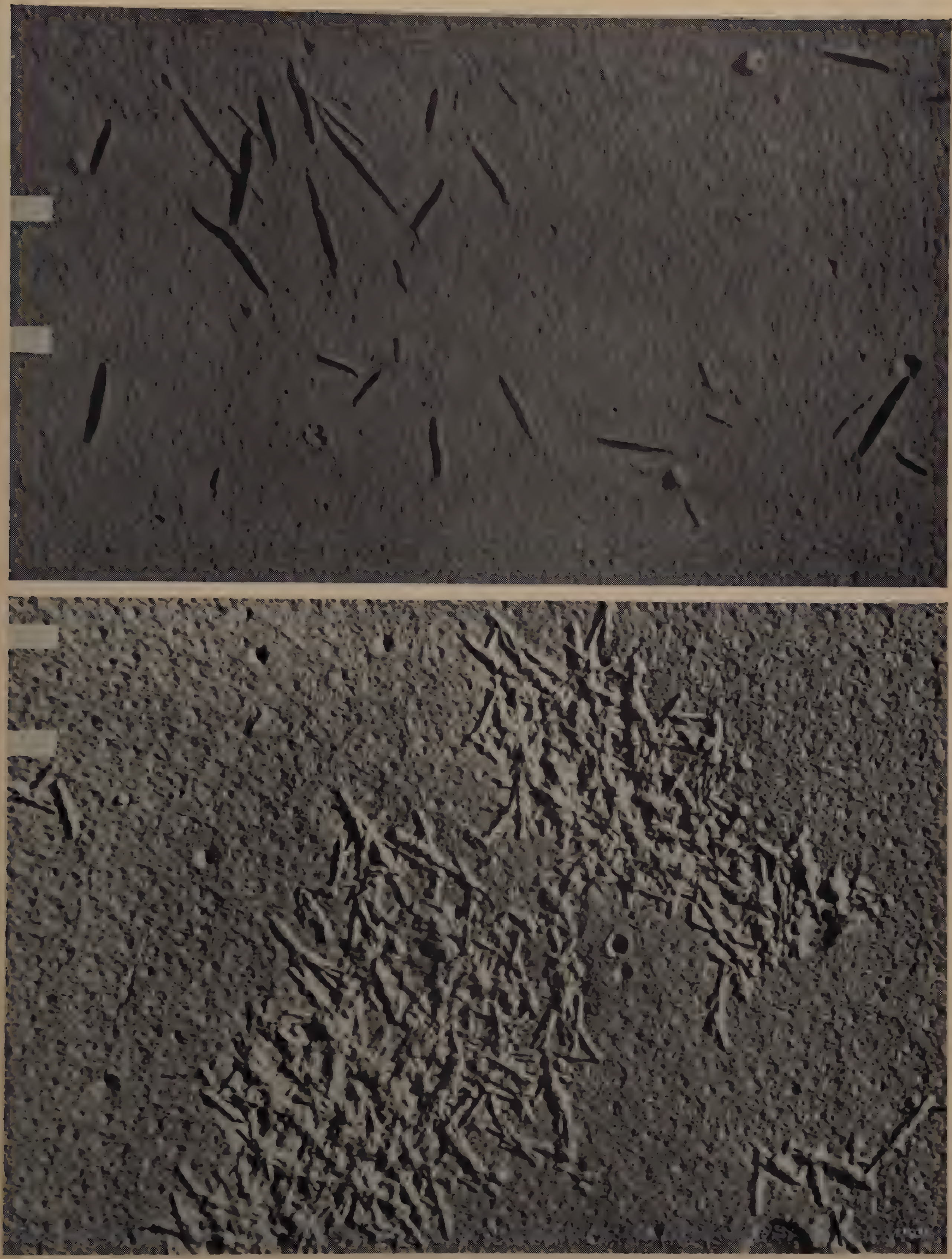

Fig. 5. *a*) Tobacco mosaic virus, obtained from tomatoes. To the solution obtained a quantity of normal serum (containing no antibodies) was added: negative serological reaction. Enlargement 18 000 ×.
b) Same virus as (*a*), showing positive serological reaction with tobacco mosaic antiserum. Enlargement 15 000 ×.

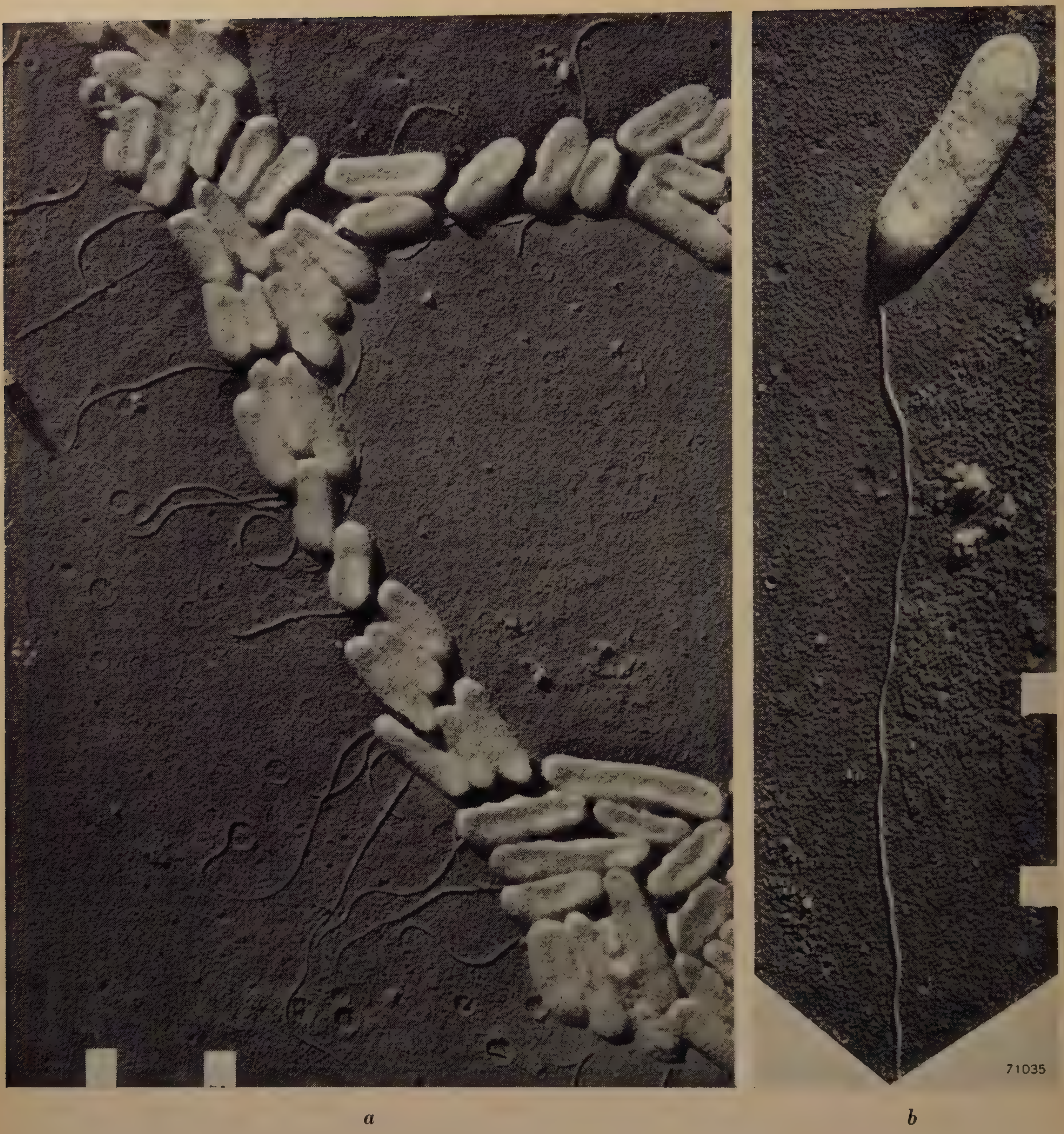

Fig. 6. Xanthomonas hyacinthi (Wakker) Dowson, the bacteria causing the Yellow disease of hyacinths. Plant tissue with bacteria in distilled water.
a) Enlargement 14 000 ×.
b) Other part of sample, enlargement 23 000 ×.

may well allow man to venture farther than ever down the fascinating road which at its end is bordered by withering crops and strangely coloured flowers, while its origin is covered by the nebulae of the problem of the nature of life itself.

Summary. Although a considerable amount of knowledge of plant viruses had already been gathered since their discovery in 1892, it was only in 1939 that for the first time virus particles were made visible to the eye. This was achieved by using the electron microscope. Ever since then, electron microscopy has been applied in phytopathology and important results have been obtained. Problems investigated with the electron microscope were, for instance: the shape and size of different kinds of viruses, the reaction of viruses with their specific antisera, the apparent crystalline form of some viruses. In this paper stress is laid on the usefulness of the electron microscope for the diagnosis of plant diseases, while at the same time essential conditions and limitations in this application are put forth. The paper is illustrated by a number of electron micrographs obtained at the Laboratory for Flowerbulb Research at Lisse with the aid of the Philips 100 kV electron microscope.

HIGH-TENSION GENERATORS FOR LARGE-PICTURE PROJECTION TELEVISION

by J. J. P. VALETON. 621.397.62:621.314.5:621.396.615.12.072.2

For the projection of television pictures which are not only large but also of high definition and brightness the cathode-ray tube requires a high voltage, of 25 to 50 kV. Generators for supplying such high voltages must conform to a number of very special requirements which have led to the development of other methods of producing such voltages than the more obvious system of stepping up and rectifying the mains supply. A few methods of achieving this purpose are outlined and one of these is described in detail.

The potentials employed for the acceleration of the electrons in television tubes have in the course of time become higher and higher. Whereas 5 kV was normal for a direct-vision tube in 1945, this was soon increased to 7 or 9 kV. Nowadays 12 kV or 14 kV is more usual and there are indications that this might be increased to even 16 or 17 kV.

This tendency towards higher potentials is the outcome of the constant demand for increased brightness, definition and dimensions in television pictures; to produce a brighter picture the cathode ray must deliver more energy to the fluorescent coating on the screen per unit of time, so that either the beam current or the acceleration voltage, or both, must be increased. A higher beam current, however, has an adverse effect on the definition, whereas a higher potential facilitates focusing, a factor which is particularly important when it is a question of tubes of the shortest possible length with a large screen. In such cases the deflection angles are wider and, in order to ensure good definition at the edges, a very slender beam must be employed; this is made possible to an increasing degree by reducing the current and increasing the acceleration voltage.

The use of a tube with a large screen is not the only means of obtaining large pictures, however. A very bright, clear picture can be produced in a tube of quite small size, and this can be reproduced on a separate screen by means of a highly efficient optical system. This is the method employed in a projection television system developed by Philips, of which a description has already appeared in this Review[1]). To be able to meet the high requirements imposed on it as regards brightness and definition, the tube in question, the MW 6-2[2]), has to operate with an acceleration voltage of 25 kV, the average current being at most 200 μA. The brightmess and definition of the picture on the screen, which is 6 cm in diameter, are sufficient to admit of optical enlargement to give a projected picture having a diagonal of 50 cm.

In recent years the Philips Laboratories at Eindhoven have evolved a projector along these lines which is capable of giving a picture measuring 3 m by 4 m. The tube employed in this equipment has a screen 12 cm in diameter and the current on which it operates is considerably higher than that of the MW 6-2; an acceleration voltage of 50 kV was found necessary to secure adequate focusing of the beam.

The above introductory remarks sufficiently illustrate the reason for the upward trend of acceleration voltages. On the other hand, however, certain inhibiting factors are encountered; according as the velocity of the electrons is increased, more power is required to deflect the beam through a given angle, and this means more expensive deflection equipment. Then again, when the acceleration potential is raised it becomes increasingly difficult to manufacture tubes that will withstand such potentials and to devise generators to supply the required voltage. Such generators form the subject of the present article.

Methods of generating high tension

Let us now review the various possibilities of developing the high potentials required for television receivers.

Rectification of A.C. voltage at mains frequency

In early television receivers the required direct voltage of 5 kV was obtained by rectifying a high alternating voltage taken from a transformer operating on the mains supply, but this has numerous disadvantages.

To secure from the low-frequency mains a rectified voltage with a sufficiently small ripple, high-value smoothing capacitors are essential and these are not only costly components, but their large store of energy may prove to be a cause of damage in the event of a breakdown in the circuit. Another drawback of the low frequency is the large number of turns required for the power transformer, made necessary by the low value of the induced voltage per turn. The heater winding for the rectifier valve, further, necessitates high-tension insulation and this, together with the H.T. winding itself, takes up a great deal of space.

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[1]) Projection-television receiver, I. The optical system for the projection, by P. M. van Alphen and H. Rinia, Philips techn. Review **10**, 69-78, 1948.

[2]) Projection-television receiver, II. The cathode-ray tube, by J. de Gier, Philips techn. Review **10**, 97-104, 1948.

Almost universally, therefore, this method of producing the required voltage was discarded as it became apparent that the high tension could be produced fairly simply as a "by-product" of the equipment serving for the magnetic deflection of the electron beam.

High tension as by-product of the deflection system

Deflection of the electron beam, both vertically and horizontally, is usually effected by means of magnetic fields generated by saw-tooth currents flowing in the deflection coils. The rapid flyback of the luminous spot from the right-hand side of the screen (end of line) to the left-hand side (start of next line) is the result of a sudden jump in the current flowing in the line-deflection coil. This simultaneously produces a voltage peak across the coil in question which may be more than 10 times higher in value than the voltage across the coil during the scanning of the line. To match the coil to the generator of the saw-tooth current a step-down transformer is connected between the two. On the primary side the peaks reach as much as 5 kV and, by extending this winding in the form of an auto-transformer, it is a simple matter to obtain still higher direct voltages after rectification, say roughly 8 kV. A rectifier circuit for voltage-doubling (cascade) then offers the possibilities of obtaining voltages up to 10 or even 14 kV.

The great advantage of this arrangement is to be found in the high frequency at which the voltage peaks occur in the horizontal deflection; with 625 (405) lines and 25 frames per second, for instance, the repetition frequency will be 625 × 25 = 15,625 c/s (405 × 25 = 10,125 c/s). Small capacitors will therefore effectively smooth the rectified voltage [3] and such capacitors are not only inexpensive but, because of their relatively low charge, they involve no hazards.

This method is particularly suitable when the power required for the electron acceleration is small compared with the reactive power used for deflection purposes, that is, so long as the first can be justifiably qualified as being a by-product of the deflection system. With direct-vision tubes this is indeed the case and where these tubes are used the method in question is therefore almost universally employed.

Rectification of separately generated pulses

The problem as applicable to tubes for projection television is rather different. Here the power required for acceleration is no longer small compared with the reactive power required for the deflection. Should it nevertheless be required to adopt the method described, the deflection equipment will have to be larger than would otherwise be necessary. Furthermore, care must be taken that fluctuations in the average beam current — which corresponds to the average brightness of the picture — cannot cause the high tension or the deflection amplitude to vary. For these reasons preference is usually given to other systems.

One such system, suitable for domestic projection television has already been described in detail in this Review [4]). In this particular instance the direct voltage is 25 kV, this being obtained from three stages in cascade. Pulses having a peak value of about 8.5 kV are fed to the first stage, these being obtained by passing a saw-tooth current through a coil. With each current pulse in the coil, which with its self-capacitance constitutes an oscillatory circuit, a damped oscillation is set up, both half cycles of which are rectified. The resonant frequency of the circuit is about 32,000 c/s, the repetition frequency with which the circuit is excited being roughly 1000 c/s.

For further details the reader is referred to the article mentioned in note [4]).

Rectification of a high sinusoidal voltage of high frequency

A fourth method consists in rectifying a high sinusoidal alternating voltage as provided by an oscillator (with or without cascade circuit). This arrangement is also sometimes met with in projection television receivers. Since the coils used are generally of the air-cored type, there is no alternative but to operate the oscillator at a frequency which is higher than required for effective smoothing, for example 300 kc/s, the size of the coils being nevertheless such that very close coupling cannot be secured; the efficiency of the oscillator is therefore fairly low and the internal resistance (on the D.C. side) high. As we shall see presently, however, a low internal resistance is essential; the higher the inherent resistance proves to be, the greater the amount of trouble involved in reducing it.

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[3]) Moreover, the ripple voltage (if not too high) interferes very little with the picture since it is synchronous with the horizontal motion of the spot.

[4]) Projection-television receiver, III. The 25 kV anode voltage supply unit, by G. J. Siezen and F. Kerkhof, Philips techn. Review **10**, 125-134, 1948.

Considerable improvement can be obtained in this respect by employing Ferroxcube magnetic materials [5]) for the oscillator coils. In this way it is possible to operate with relatively low frequencies (some tens of kc/s) without the need for coils of large dimensions [6]), at the same time ensuring low magnetic losses in the core and low dielectric losses in the insulation. From the point of view of smoothing, there is no object in employing a higher frequency, since a certain amount of reserve capacitance is in any case essential to meet the fluctuations in the load.

In the following this method of producing high tension is discussed in greater detail, this being followed by a description of two existing designs for the supply of 50 kV high tension. First, however, let us review the electrical requirements to be imposed on H.T. generators for television receivers.

Electrical requirements to be met by a T.V. high-tension generator

In the first place the generator must naturally be capable of delivering the required amount of current at the voltage desired. As far as the current is concerned, it is usual to base this on the highest mean value of the beam current for which the tube is rated; the peaks may be several times higher. It is often stipulated that the generator must be able to supply this mean current ($I_{0\,\mathrm{max}}$) at the nominal value of the acceleration voltage ($V_{0\,\mathrm{nom}}$); further that the voltage shall drop rapidly in the event of the current assuming a constant higher level (so that the short-circuit current will not largely exceed $I_{0\,\mathrm{max}}$), and that the no-load voltage shall be little greater than $V_{0\,\mathrm{nom}}$. *Fig. 1* illustrates the required relation between the voltage V_0 and the current I_0. A characteristic of this kind provides as it were a safety precaution against overloading of the screen of the cathode-ray tube.

For so far as the instantaneous value of the current, relating to the high lights of the picture, exceeds the average, the current is supplied by a reservoir capacitor. Sometimes the usual capacitors in the rectifier circuit will provide sufficient reserve capacitance, or the anode capacitance of the tube itself may fulfil this function, but, if not, extra capacitance must be provided, as will be shown presently.

In the second place, the internal resistance is very important. It has already been mentioned that this resistance should be low, i.e. that the characteristic (fig. 1) should be roughly horizontal from $I_0 = 0$ to $I_0 = I_{0\,\mathrm{max}}$. The reason for this is two-fold.

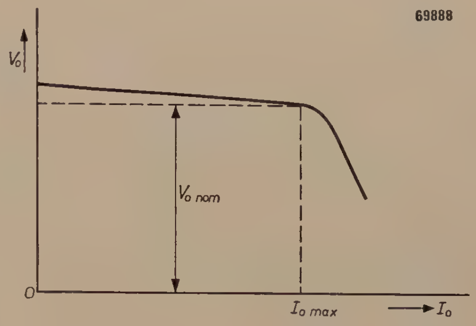

Fig. 1. Desired V_0-I_0 characteristic for an H.T. generator for television receivers. The no-load voltage should be but little more than the voltage $V_{0\,\mathrm{nom}}$ relating to the highest average current $I_{0\,\mathrm{max}}$ of the tube, and should drop rapidly when more current than that is taken.

In television tubes the electron beam is generally focused by means of a magnetic "lens". The power of this lens is dependent on the acceleration voltage; if this voltage varies, for example as a result of a change in the average brightness of the picture, adjustment must also be effected to keep the definition as high as possible. Hence, if the internal resistance is too high, the focus must be constantly readjusted.

The other consideration concerned is that, in the magnetic deflection employed with most tubes today, the deflection angle is also dependent on the acceleration voltage. (This angle is inversely proportional to the square root of the acceleration voltage). If this voltage varies, the picture size will fluctuate and this is quite as unpleasant as a varying focus.

To obviate these defects care should be taken to ensure that the acceleration voltage varies as little as possible with the current or, in other words, that the internal resistance of the generator shall be as low as possible.

Some further aspects of an H.T. generator comprising an oscillator and a rectifier

Let us now look a little more closely at the last mentioned method of producing an H.T. voltage, taking first the rectifier, then the oscillator and, finally, measures to ensure low internal resistance.

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[5]) J. L. Snoek, Non-metallic magnetic material for high frequencies, Philips Techn. Review **8**, 353-360, 1946, and W. Six, Some applications of Ferroxcube, Philips techn. Review **13**, 301-311, 1952 (No. 11).

[6]) The possibilities in this direction were indicated by P. J. H. Janssen of the Television Development Laboratory, Eindhoven.

The rectifier

As starting point we will take the simplified circuit depicted in *fig. 2a*, in which L-C is the oscillatory circuit, D is a diode and C_1 is a smoothing capacitor. This oscillatory circuit is regarded at the same time as part of the rectifier circuit, because a conclusion will be drawn about the values of L and C from the following considerations.

The time t is taken to be zero at the instant when the voltage v across the oscillatory circuit is zero and on the verge of becoming positive (i.e. when the side of C that is connected to the anode becomes positive with respect to the other side). The voltage v is thus represented in the first instance by: $v = V \sin \omega t$ (fig. 2*b*) and, disregarding the losses in the circuit, the current i will be: $i = I \cos \omega t$ (fig. 2*c*). In this, V is the peak value which the voltage would attain in the absence of the rectifier; I denotes the peak value of the current and ω the natural angular frequency of the oscillatory circuit.

As soon as v becomes equal to the potential across the smoothing capacitor, the diode passes current. For the sake of convenience we will regard the capacitor C_1 as being so large that the current pulses from the diode do not substantially alter the voltage across C_1; in other words, that a direct voltage (V_0), the ripple of which may be disregarded, occurs across C_1. We shall also disregard the voltage drop across the diode when current is passing. As long as current flows in the diode, the voltage across C and L will therefore be the direct voltage V_0.

The fact that the voltage across C is constant means that no current passes through this capacitor, that is, that the current i flowing in L passes in its entirety through the diode. The constant voltage across L implies that this current i (which is equal to the diode current i_d, fig. 2*d*) decreases linearly with time.

The phase angle ωt at which the diode begins to pass current will be denoted by $\pi/2 - \varphi$; then:

$$V_0 = V \cos \varphi \;, \quad . \;.\;.\;.\;.\;.\;. \quad (1a)$$

the initial value I_d of the diode current being

$$I_d = I \sin \varphi \quad . \;.\;.\;.\;.\;.\;. \quad (1b)$$

When $t = 0$, only magnetic energy exists in the oscillatory circuit, namely: $\frac{1}{2} LI^2$. A part of this, viz. $\frac{1}{2} CV_0^2$, appears as electric energy in the capacitor C, whilst the remainder, $\frac{1}{2} LI_d^2$, is applied to the smoothing capacitor by way of the diode. Hence:

$$\tfrac{1}{2}LI^2 = \tfrac{1}{2}CV_0^2 + \tfrac{1}{2}LI_d^2 \,.$$

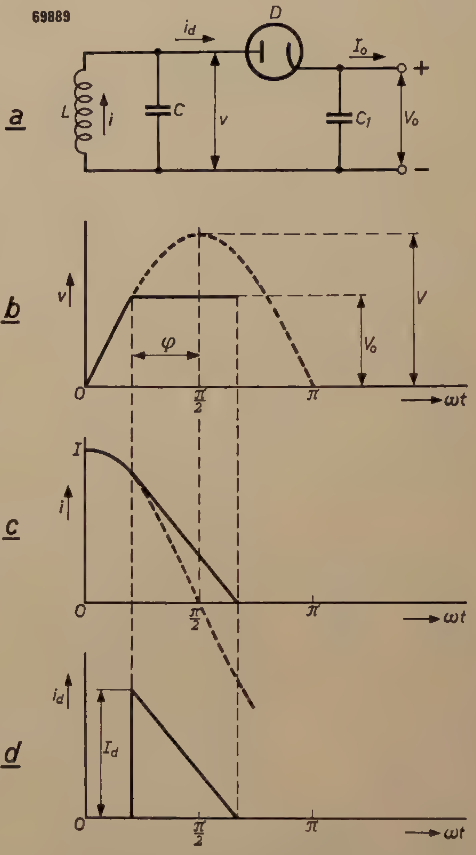

Fig. 2. *a*) Circuit of an H.T. generator. L-C = oscillatory circuit forming also part of the oscillator. D = diode; C_1 = smoothing capacitor.

The following quantities are shown as functions of ωt: *b*) the the voltage v across the L-C circuit; *c*) the current i flowing in inductance L; *d*) the current i_d passing through the diode. The curves are not continued beyond the point where i_d becomes zero.

In conjunction with (1b) this gives:

$$I_d^2 = \tan^2\varphi \cdot \frac{C}{L} V_0^2 . \;.\;.\;.\;.\;.\;. \quad (2)$$

Let f denote the frequency with which the cycle is repeated; the capacitor C_1 then receives f times the energy $\frac{1}{2} LI_d^2$ per second and, in the same interval, the energy $I_0 V_0$ is withdrawn from it (I_0 is the mean value of the direct current). In the stationary condition, then:

$$f \cdot \tfrac{1}{2}LI_d^2 = I_0 V_0 \;.\;.\;.\;.\;.\;. \quad (3)$$

If φ is small, i.e. as long as C_1 is in parallel with C only for a small fraction of the cycle, we may say as an approximation that

$$f = \omega/2\pi = 1/(2\pi\sqrt{LC}).$$

From (3) it then follows that:

$$I_d^2 = 4\pi \sqrt{\frac{C}{L}}\, I_0 V_0 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Elimination of V_0 from (4) and (2) gives:

$$\tan\varphi = 4\pi \frac{I_0}{I_d}, \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and subsequent elimination of I_d^2 gives:

$$\sqrt{\frac{L}{C}} = \frac{\tan^2\varphi}{4\pi} \cdot \frac{V_0}{I_0} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

These equations will serve as a guide in the design. For I_0 and V_0 we take the highest mean current $I_{0\,\max}$ and acceleration voltage $V_{0\,\text{nom}}$ required for the cathode-ray tube; we first decide upon $\tan\varphi_{\max}$, that is, the value of $\tan\varphi$ which corresponds to $I_0 = I_{0\,\max}$, taking into consideration the following.

Under the no-load conditions the direct voltage is equal to the peak value V of the alternating voltage, whilst on full load it is equal to $V\cos\varphi$. Now, in order to keep the internal resistance of the generator as low as possible without resorting to special measures, $\varphi_{\max}$ should be made as small as possible, for the difference between V and $V\cos\varphi_{\max}$ will then be at a minimum. A lower limit for $\varphi_{\max}$ may be derived from (5) by taking for I_d the maximum permissible peak current for the particular diode used; at lower values of $\varphi_{\max}$ the diode would be overloaded.

Another consideration, however, prompts us not to take $\varphi_{\max}$ to the lower limit; the efficiency is impaired when $\varphi_{\max}$ is reduced, as will be seen from the following. In contrast with what has been assumed, the oscillatory circuit is in actual fact subject to certain losses. For a given (finite) quality, a certain part of the energy $\frac{1}{2}LI^2$, which is available when $t = 0$, is lost every cycle. The smaller the value of $\varphi_{\max}$, the smaller also the fraction of $\frac{1}{2}LI^2$ delivered per cycle by the diode, and the more unfavourable the ratio of this fraction to the losses. From the point of view of efficiency, the indicated procedure is therefore to employ a high value of $\varphi_{\max}$.

A compromise must therefore be sought, and a suitable value for $\tan\varphi_{\max}$ will usually lie somewhere between 0.2 and 0.5.

When $\tan\varphi_{\max}$ has been fixed, equation (6) gives the value of $\sqrt{L/C}$. By fixing a value for f as well, $\sqrt{LC}$ is determined and hence L and C are known individually. With regard to the choice of f, the following should be noted.

In the foregoing if has already been said that a high frequency is favourable from the point of view of smoothing. L and C, or at any rate LC, will then be small. But a disadvantage of a high frequency is that the losses in coils usually increase with frequency. By way of example, *fig. 3* illustrates the measured ratio of the loss resistance r to the inductance L of a disc type of coil, as a function of frequency. In order to keep the losses within bounds, then, the frequency should not be too high, but should preferably be above the highest audible frequency, so that whistles may be avoided in the possible event of mechanical vibration of any of the components.

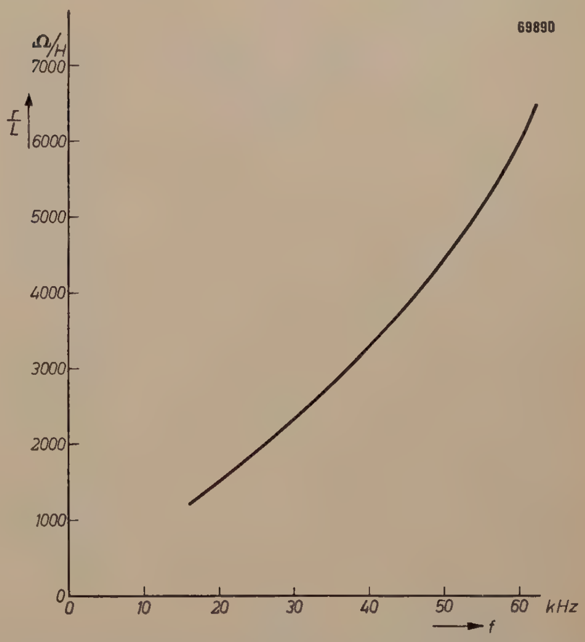

Fig. 3. Ratio of the loss resistance r to the inductance L as a function of the frequency f in a disc type of coil with Ferroxcube core.

The value of C as derived from $\sqrt{L/C}$ and $\sqrt{LC}$ should of course not be less than the sum of the self-capacitance of the coil and the input capacitance of the rectifier. The last-mentioned contribution may be appreciable in the case of a cascade circuit using a large number of diodes. In the H.T. generators constructed in the laboratory we have endeavoured to arrange matters so that the input capacitance of the rectifier and the self-capacitance of the coil together just equal the computed value of C, thus dispensing with the need for an extra capacitor. This is worth doing, seeing that a capacitor suitable for the high voltages and high frequency in question is a costly item [7]).

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[7]) It would of course be possible to connect a low-voltage capacitor of higher value across a part of the coil, but, owing the fact that the coupling between the coil sections is never perfect, this might give rise to parasitic oscillations. In view of this such a solution is better avoided.

The preferred frequency is between 20 and 30 kc/s, in which range the use of Ferroxcube for the cores has many advantages [8]). Compared with air-cored coils, fewer turns of wire are required in order to secure the desired inductance, whilst coupling between sections of the coil mutually and between the coil and other windings (which we shall discuss presently) is much closer. The eddy currents in Ferroxcube are negligible, moreover, so that in the frequency range concerned it is only necessary to take into consideration the hysteresis losses and dielectric losses in the insulation. In view of the hysteresis losses in particular, the flux density should not be too high, say, 0.10 to 0.15 Wb/m². The insulating material should have only a small loss angle.

So much then for the circuit employing a single stage of rectification (fig. 2*a*). The required direct voltage may, however, be so high that equation (6) will yield an impracticably high value of L/C, in which case the solution lies in the use of a cascade circuit, in which the total direct voltage is a multiple of the voltage V_0 in equation (6).

For details of the cascade arrangement the reader is referred to the article mentioned in note [4]), having regard to the fact that in the instance in question the alternating voltage applied to the input is a damped oscillation; in the present case we are concerned with an undamped oscillation.

The oscillator

In our discussion of the kind of rectifier depicted in fig. 2*a*, we have assumed that, at a time $t = 0$, a current I flows in the coil, without considering the manner in which this current originates. In the half-cycle during which the voltage v is positive — and if a cascade circuit is used, in the other half-cycle as well — the oscillatory circuit delivers energy to the rectifier, but energy is also lost through the losses in the network. If this were not replaced, the current, after one cycle, would be less than the original value I.

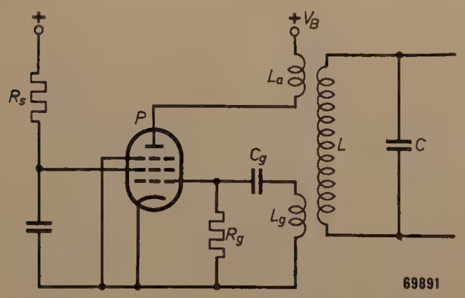

Fig. 4. Oscillator circuit. P = pentode with anode and control grid circuits coupled by means of the coils L_a and L_g to the oscillator circuit L-C (cf. fig. 2*a*). C_g = grid capacitor. R_g = grid leak. R_s = resistor in series with the screen grid.

It is the function of the oscillator to supply to the circuit just so much energy per cycle as is delivered and lost, so that the current in the coil will return to the value I at the commencement of every cycle.

A simple oscillator circuit is depicted in *fig. 4*. Both the anode and control grid circuits of a pentode are coupled inductively to the L-C circuit in such a way as to ensure positive feedback. The circuit operates on the class C principle, that is, anode current flows for less than half a cycle. During the time that current flows, the anode voltage V_a is lower than the supply voltage V_B (*fig. 5*) and energy is then supplied to the circuit.

To improve efficiency it is useful to limit the passage of current to a mere fraction of a half-cycle.

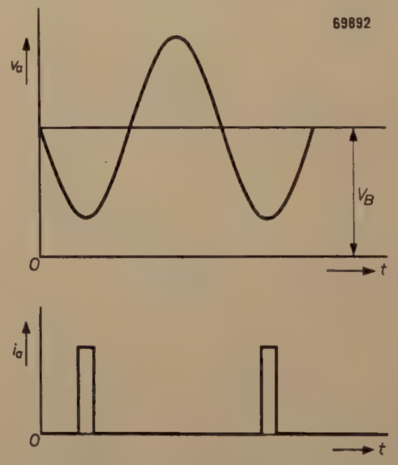

Fig. 5. Anode voltage v_a and pulsatory anode current i_a of the pentode P (fig. 4) as functions of time t (class C operation). The pulse i_a as shown in the diagram is exaggeratedly narrow.

That this does favour the efficiency may be seen from the following. Suppose that the anode-current pulses are so narrow that during these periods the current as well as the voltage may be regarded as constant, as in fig. 5. It is then a question of the ratio of the energy delivered to the oscillatory circuit per cycle, to the energy dissipated at the anode in the same period. From the above premise it follows that this ratio is the same as the ratio of the voltages v_{L_a} (across the coupling coil L_a) to v_a, both as regarded at the instant of the pulse. This ratio and accordingly also the efficiency is greatest when v_{L_a} is at its maximum, and v_a at a minimum, that is to say, when the anode current pulse occurs at the time when v_a is lowest. If the pulse be made any wider, so that v_a and v_{L_a} can no longer be regarded as constant during the period of the pulse, v_{L_a} and v_a in the above-mentioned energy ratio must be replaced by an average in respect of the duration of the pulse. This average will be less than the maximum for v_{L_a} and above the minimum for v_a, so that the ratio is then not so favourable.

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[8]) See article by W. Six referred to in note [5]).

Class C operating conditions are ensured by seeing that the alternating voltage across the coil L_g is several times greater than the grid base of the pentode.

A variable load on the H.T. generator will mean variable damping in the oscillator circuit or, generally speaking, variations in the amplitude of the alternating voltage, manifested as a fluctuating direct voltage. Apart from special measures to ensure a constant direct voltage, as discussed in the next section, precautions can be taken in the design of the oscillator itself to make the alternating voltage as independent as possible of the damping by suitably limiting the amplitude.

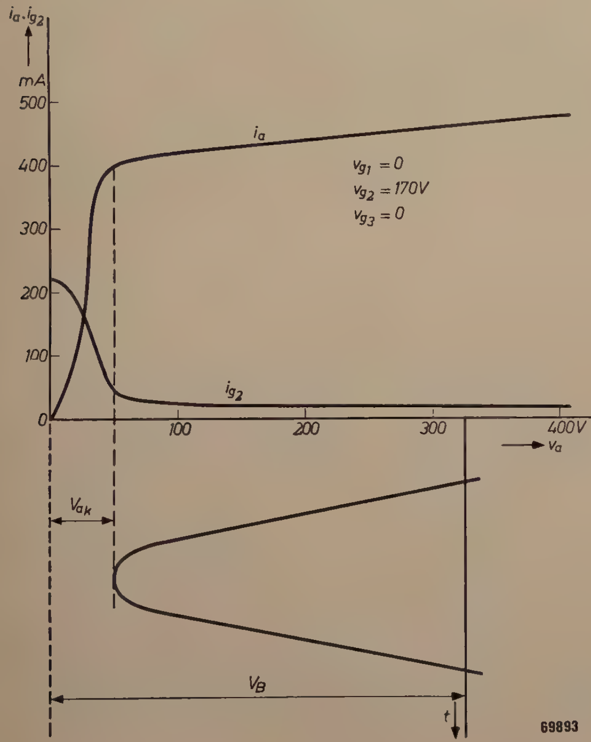

Fig. 6. Anode current i_a and screen grid current i_{g2} of the pentode PL 81 as functions of the anode voltage v_a, with constant screen voltage $V_{g2} = 170$ V and zero volts on control and suppressor grids.

In the oscillator, v_a varies with the time t sinusoidally about the value V_B. The amplitude as shown is so large that the minimum of v_a lies just at the bend in the i_a-v_a characteristic (V_{ak}). In this way the amplitude of v_a is limited.

When an oscillator is switched on, the voltage amplitude rapidly increases up to the point where it is limited by one factor or another. For our particular purpose this limitation can best take place by the bend in the anode current i_a versus anode voltage v_a characteristic of the pentode, the grid potentials being constant (*fig.* 6). Limitation is established by reason of the fact that when the amplitude of the alternating anode voltage increases, the minimum of v_a ultimately becomes so small that it lies at the bend in the i_a-v_a curve. Any further increase in the amplitude is checked because v_a would enter the zone in which i_a drops rapidly with decreasing v_a.

The limiting effect can be increased taking advantages of fact that, below the bend in the curve, the screen-grid current i_{g2} rises sharply at the expense of i_a when v_a drops. If the screen grid is fed through a resistor (R_s, fig. 4), the screen voltage will drop when amplitudes greater than that shown in fig. 6 occur. In consequence, the i_a-v_a characteristic is displaced to a lower level and i_a decreases to a greater extent than if the screen voltage were constant.

If the coils L and L_a (fig. 4) are very closely coupled — and this is quite possible when Ferroxcube cores are used — the amplitude V of the alternating voltage across the L-C circuit, and therefore also the direct voltage, will be nearly enough proportional to the amplitude of the alternating anode voltage. In the event of small variations in the last-mentioned voltage, V_0 will also vary but slightly.

The circuit can best be so constituted that when the direct current withdrawn from it is at a maximum (that is, with maximum damping of the oscillatory circuit), the minimum value of v_a will lie just at the bend in the i_a-v_a curve. On smaller loads the amplitude of the alternating anode voltage will tend to increase, since, per cycle, more energy is then supplied to the oscillatory circuit than is being taken from it. This would result in an undesirable increase in the rectified high tension, but the limiting devices described above ensure that the slightest increase in the amplitude of the alternating anode voltage results in a decrease in anode current, sufficient to restore equilibrium between the energies received and delivered per cycle. The curve representing i_a as a function of time then reveals a dip which is so much the deeper according as the direct current is lower (*fig.* 7).

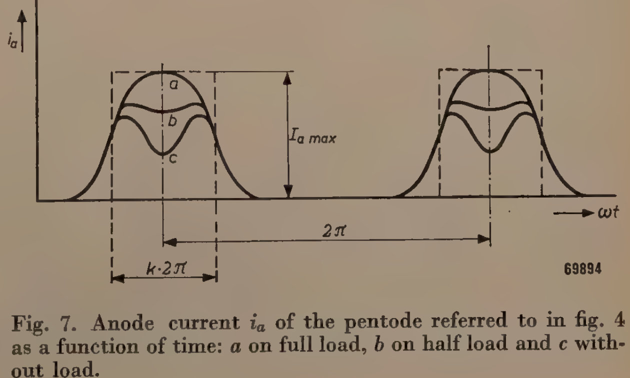

Fig. 7. Anode current i_a of the pentode referred to in fig. 4 as a function of time: a on full load, b on half load and c without load.

In the circuit under review the pentode used should preferably be one that will pass a heavy anode current at quite a low anode potential. At the same time, the bend in the i_a-v_a characteristic should be as sharp as possible and should occur at a low value of v_a. The pentode PL 81 satisfies these conditions.

In order to facilitate computation of the oscillator circuit we replace the form of the anode current on full load by a rectangle (dotted lines in fig. 7) whose height is equal to the maximum value of $I_{a\,\max}$ of the anode current and the width such that the area of the rectangle is the same as that of the actual wave-form of the current. This width is taken to be k times the duration of a cycle, k being usually 0.20 to 0.25.

As a further approximation we assume that, when current is flowing, the average anode voltage is equal to the voltage V_{a_k} at which the bend in the curve occurs. The oscillatory circuit thus receives an amount of energy $kI_{0\,\max}\,(V_B - V_{a_k})$ per cycle or, expressed in power, $fkI_{a\,\max}(V_B - V_{a_k})$. The power delivered by the oscillator is $I_{0\,\max}\,V_{0\,\mathrm{nom}}$. The efficiency will be denoted by η_a, disregarding the heater and screen-grid-current; hence:

$$\eta_a fkI_{a\,\max}\,(V_B - V_{a_k}) = I_{0\,\max}\,V_{0\,\mathrm{nom}}.$$

This equation may be employed to estimate $I_{a\,\max}$ for the purposes of the design when $I_{0\,\max}$, $V_{0\,\mathrm{nom}}$ and V_{a_k} are known, values for V_B and f are decided upon and η_a and k can be evaluated in accordance with experience. Practical values of k have already been indicated; η_a usually lies between 0.3 and 0.6, dependent on the value of tan φ and the quality factor of the coil (see above).

The value of $I_{a\,\max}$ obtained in this manner may exceed the rated value for the valve in question, but in this case two or more valves can be employed, either in parallel or, if an even number, in push-pull.

Reducing the internal resistance

Although the above-mentioned methods of limiting the amplitude of the alternating voltage already considerably assist in keeping down the internal resistance of the generator, they are not generally adequate if requirements as laid down are very stringent.

In such cases automatic voltage control is applied. The H.T. voltage is then regulated by a control voltage which is varied automatically in such a way that the high tension remains reasonably constant on varying loads.

Voltage control of this kind in no way minimizes the usefulness of the methods of avoiding variations in the output already referred to (choice of $\varphi_{\max}$, limitation circuit in the oscillator), for, if such precautions are neglected, a possible defect in the automatic control might cause the voltage to exceed the safe limits.

There is a choice of methods of obtaining the necessary control voltage, viz. this voltage may be:

a) proportional to the high tension or to the difference between this and a constant reference voltage;
b) proportional to the output current of the generator;
c) made up of the sum of two voltages, one of which is obtained as in (a), the other as in (b).

Method (a) has the advantage that it ensures high stability, but it does not admit of making the internal resistance zero or negative. This is possible with method (b), but here there is some risk of instability. The combined method (c) frequently affords a satisfactory combination of the advantages of (a) and (b).

Similarly, the control voltage can be made to operate on the high tension in different ways, and examples will now be given of two such methods as applied to 50 kV generators made at the Philips Laboratories at Eindhoven.

1) The first of the control circuits described in the following refers to a 50 kV generator giving a maximum mean current of 0.45 mA. The control voltage is obtained by passing the current I_0 through a resistor (R_r, *fig. 8*), that is, in accordance with method (b) above. This voltage is part of the grid potential of a triode, the anode circuit of which is coupled to the oscillatory circuit *L-C* of the H.T. generator. The triode, or "damper" valve, exercises control on the voltage by reason of the amount of damping which it affords, dependent on whether the grid voltage is high or low. When the load is reduced, and with it the corresponding part of the total damping of the oscillator, $|V_r|$ is so reduced that the valve in question provides an equivalent amount of damping, the overall damping thus remaining constant.

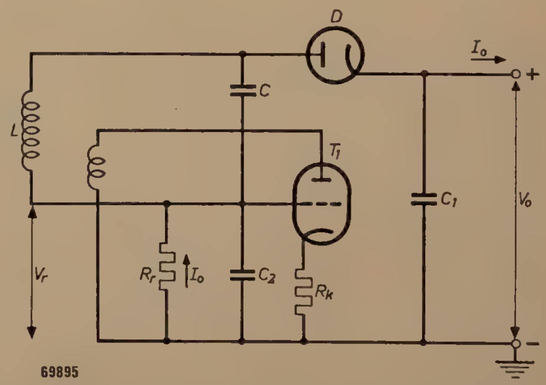

Fig. 8. Circuit of H.T. generator in which the voltage V_0 is maintained at a constant level by a "damper" valve T_1. R_r = resistor across which the control voltage $V_r = I_0R_r$ occurs. C_2 = smoothing capacitor. R_k = bias resistor. For meanings of the remaining symbols see figs. 2 and 4.

An advantage of this arrangement is that the power taken by the oscillator from the source of supply is constant. Should the internal resistance of this source be on the high side, it would have no effect on the internal resistance of the H.T. generator. It is of course a drawback that the extra valve must be capable of dissipating considerable power, namely $V_{0\,\mathrm{nom}} \times I_{0\,\mathrm{max}}$ (in our example 22.5 W), for which reason this method is suitable only in cases where the power generated is not very high.

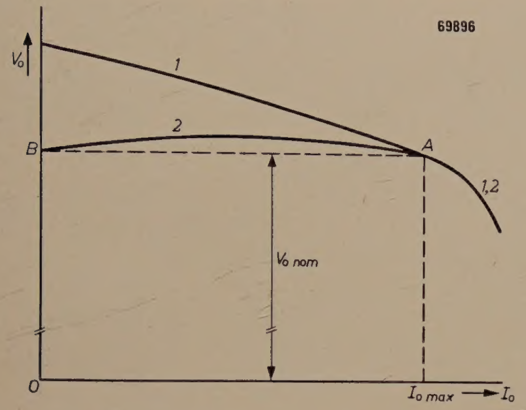

Fig. 9. Curves representing $V_0 = f(I_0)$ of an H.T. generator: *1* without, *2* with automatic voltage control.

The adjustment of the circuit is quite simple. In *fig. 9* (*1*) shows the curve $V_0 = f(I_0)$ without voltage control; the curve is such that the nominal voltage $V_{0\,\mathrm{nom}}$ is available (point *A*) when the maximum current $I_{0\,\mathrm{max}}$ flows. Let us now see what happens when the control becomes operative. Under no-load conditions no current passes through the resistor R_r (fig. 8), in which case the voltage between grid and cathode of the damper valve is only as provided by the biasing resistor R_k. This resistor ensures a bias that will make the no-load voltage of the generator equal to $V_{0\,\mathrm{nom}}$; the triode used for the damping then introduces just as much damping in the oscillatory circuit as the rectifier does on full load. The curve showing $V_0 = f(I_0)$ with control operating (*2*), thus passes through the point *B* (fig. 9), which is level with *A*.

When the generator is placed under load, current flows through R_r, the bias is increased and the damping effect of the triode is reduced. The value of R_r should be so adjusted, that the triode just fails to pass current and therefore affords no damping when the generator is fully loaded. Curve *2*, then, also passes through the point *A*.

In the ideal case, the characteristic would be the straight line *BA*. However, since not all effects in the circuit are linear functions of the control voltage V_r, the characteristic is usually somewhat curved, as in *2*, fig. 9. On small loads the internal resistance of the generator is then negative (increasing voltage with increasing current). So long as the absolute value of this resistance is not too high, there will be no instability, owing to the positive resistance of the load.

Let us for a moment suppose that the triode is replaced by a resistance equal to the average internal resistance R_i of the triode, at the grid bias that occurs when the generator is not under load ($V_r = 0$). Taking into account the fact that the triode passes current every other half cycle only, the power dissipated will be:

$$W_a = \tfrac{1}{2}\,\frac{V_{a\,\mathrm{rms}}^2}{R_i},$$

where $V_{a\,\mathrm{rms}}$ is the r.m.s. value of the alternating voltage in the anode circuit. Since W_a is known ($= V_{0\,\mathrm{nom}} \times I_{0\,\mathrm{max}}$), we thus also know the appropriate value of $V_{a\,\mathrm{rms}}$ to meet our requirements.

In order to avoid dissipating the whole of the power by the triode, a resistor may be placed in series with this valve to absorb some of the power. Nevertheless, it may be found necessary to use two or more valves in parallel or push-pull.

2) The second method of providing automatic control, which we shall now discuss[9]), was incorporated in a generator for 50 kV, 1.5 mA. Owing to the amount of power involved (75 W), the use of a damper valve is no longer suitable.

The control voltage obtained by the above-mentioned combined method (c) operates on the control grid of the oscillator valve. The circuit is reproduced in *fig. 10*.

The current I_0 is passed through a resistor R_r; the higher the current, the greater the grid bias applied to a small triode T_2. The potential of the anode (point *x*) reproduces in an amplified form the fluctuations in the voltage I_0R_r with the correct

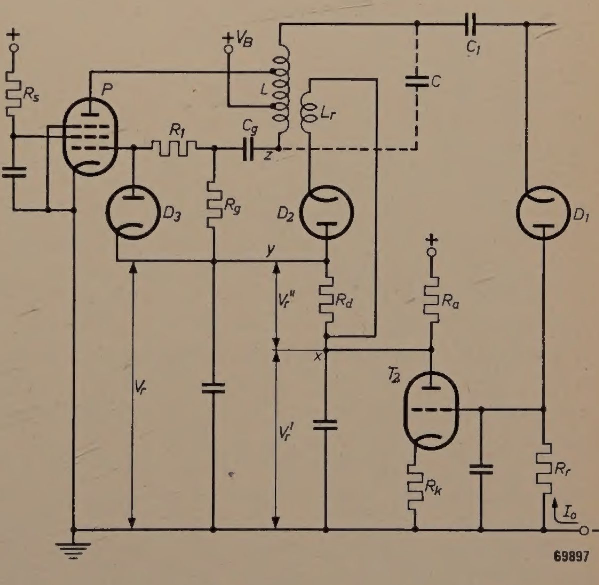

Fig. 10. Circuit of H.T. generator with stabilised voltage, with control voltage V_r applied to the grid of the oscillator valve *P*.

V_r consists in part of V_r', which depends on the current I_0, and in part of V_r'', which is proportional to the voltage V_0.

T_2 = auxiliary triode. D_2, D_3 = auxiliary diodes. R_a = load resistor. R_d = resistor across which the voltage V_r'' is produced by the rectified current from D_2. R_1 = resistor for flattening the positive peaks of the alternating voltage at the grid of *P*. Of the cascade rectifier only the first capacitor (C_1) and first diode (D_1) are shown. For the remaining symbols see figs. 2 and 4.

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[9]) Developed by L. J. van de Polder of the Research Laboratory, Eindhoven.

sign for the voltage V_r' between x and earth to be used as control voltage for the grid of the oscillator valve. The level of the potential at x is too high, however, and a second potential, of opposite polarity, is used in conjunction with the first. This latter potential is obtained by rectifying (diode D_2) the alternating voltage induced in a winding L_r which is coupled to the coil L. The direct voltage component V_r'' then occuring across R_d is of a value and polarity that will give the point y (fig. 10) a negative potential with respect to the cathode of P (earth).

The action of the circuit is as follows. On increasing loads, I_0R_r rises, the anode current of T_2 drops, the potential at point x increases and, assuming V_r'' to be constant, that of y rises to an equal extent. As a result, the oscillatory circuit receives more power to meet the increased load.

Actually, V_r'' is not constant, however, but is proportional to the alternating voltage across L_r, that is, to the alternating voltage across the L-C circuit, and, therefore, also to the voltage V_0 to be controlled. This proportionality is to our advantage, since negative feedback occurs by way of V_r'', which counteracts variations in V_0 and thus promotes stability.

The circuit is so adjusted that on full load the point y is just at earth potential (it must not be at a higher potential as this precludes any controlling action), and that on full load the potential of y will have dropped to the extent that the L-C circuit receives just enough power to produce the same high tension $V_{0\,\mathrm{nom}}$ as on full load. This is easily arranged by employing suitable values of R_r, R_k and R_a (fig. 10).

To mention one or two details of the circuit shown in fig. 10, the diode D_3, in conjunction with resistors R_g and R_1 ensures that the control grid assumes the potential of point z when the positive peaks of the alternating voltage occur at the point z. This potential will then determine the amount of power applied to the L-C circuit.

Resistor R_1 ensures that the alternating voltage component at the control grid shall not be sinusoidal (as at x), but that it takes the form of flattened peaks, thus improving the waveform of the anode current of the pentode.

Two practical examples

In conclusion, particulars will now be given of the two 50 kV generators constructed in the laboratory for the purpose of carrying out tests with large-screen projection television (approx. 3 m × 4 m).

50 kV, 0.45 mA

This generator, which has air-insulation and which employs the principle of constant damping, is depicted in *fig. 11*. The rectifier (on the right in the photograph) consists of four stages in cascade, each using a DY 30 diode. Each of the valve holders in the rectifier is enclosed in a well rounded-off brass ring to avoid corona. The valves and capacitors of the rectifier are enclosed between plates of polystyrene.

The filaments of the diodes, which consume only 0.25 W each, are fed with high-frequency current supplied by the oscillator; the filaments of the first and second diode are each fed from a specially insulated winding coupled direct to the main coil, but the feed of the third and fourth diodes is taken from a separate insulating transformer in order to divide the wide difference in potential between these filaments and earth. The transformer consists of a closed magnetic circuit of Ferroxcube carrying a primary and two secondary windings, each of which comprises only a few turns of insulated wire. The oscillator frequency is 24 kc/s.

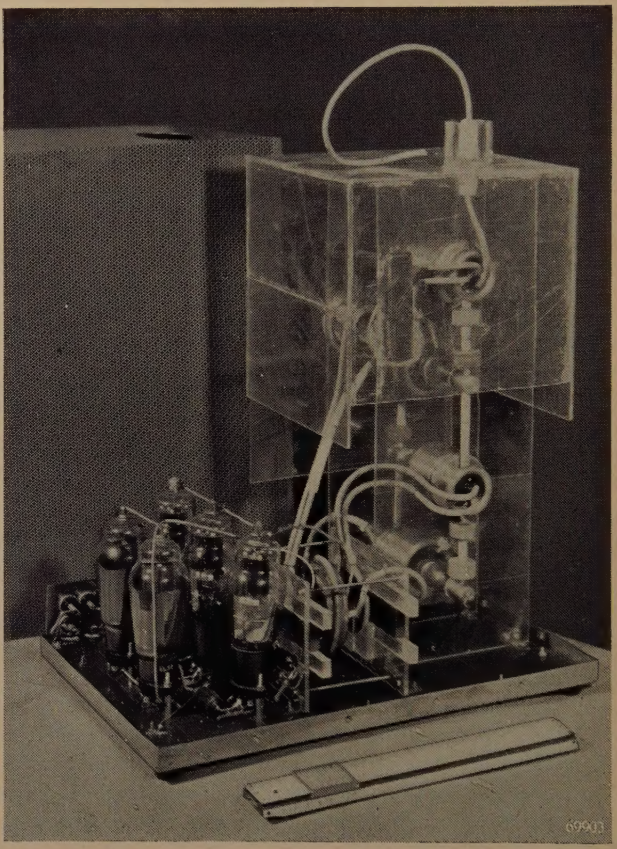

Fig. 11. Experimental 50 kV, 0.45 mA H.T. generator. From left to right the two damping valves in parallel, the three oscillator valves in parallel, the oscillator coil and, between polystyrene plates, the rectifier (four diodes DY 30 in cascade).

Fig. 12 shows the measured characteristic $V_0 = f(I_0)$; with no load, V_0 is only 2% above the nominal value of 50 kV. The figure also shows the total direct anode current I_a taken from a 500 V source; because of the automatic control on the damping, this current — of roughly 120 mA — is practically independent of I_0.

The efficiency on full load is found to be:

$$\eta_a = \frac{50\,000\times 0.45\times 10^{-3}}{500\times 120\times 10^{-3}} \times 100\ \% = 37.5\ \%.$$

50 kV, 1.5 mA

Fig. 13 shows the 50 kV, 1.5 mA generator, also in experimental form. In this case the oscillator coil and cascade circuit are immersed in transformer oil, thus making it possible to employ smaller components (paper capacitors; EY 51 diodes); the complete unit accordingly gains in compactness.

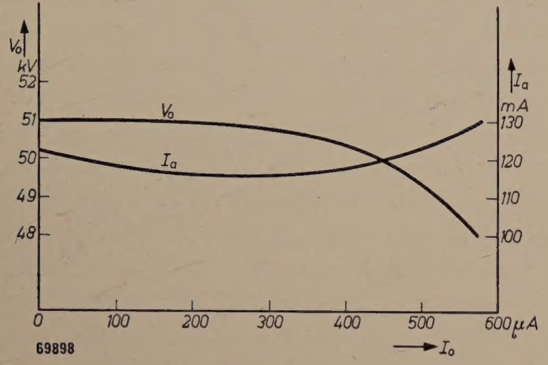

Fig. 12. D.C. voltage V_0, input and total anode current I_a drawn from a 500 V source, as functions of the load current, I_0, of the generator shown in fig. 11.

The cascade circuit comprises six stages mounted in a circle around the coil, the voltage increasing in a clockwise direction. This arrangement was adopted in order to ensure that the leads to the diodes, the heaters of which are again fed from the oscillator, would be as short as possible. The oscillator coil is of a conventional type with oiled-paper insulation and Ferroxcube core; the frequency is about 30 kc/s.

On the chassis in the upper left-hand corner of the photograph will be seen the four oscillator valves PL 81, connected in push-pull and parallel, together with the triode, diodes and other components of the control circuit, the basic diagram of which is reproduced in fig. 10.

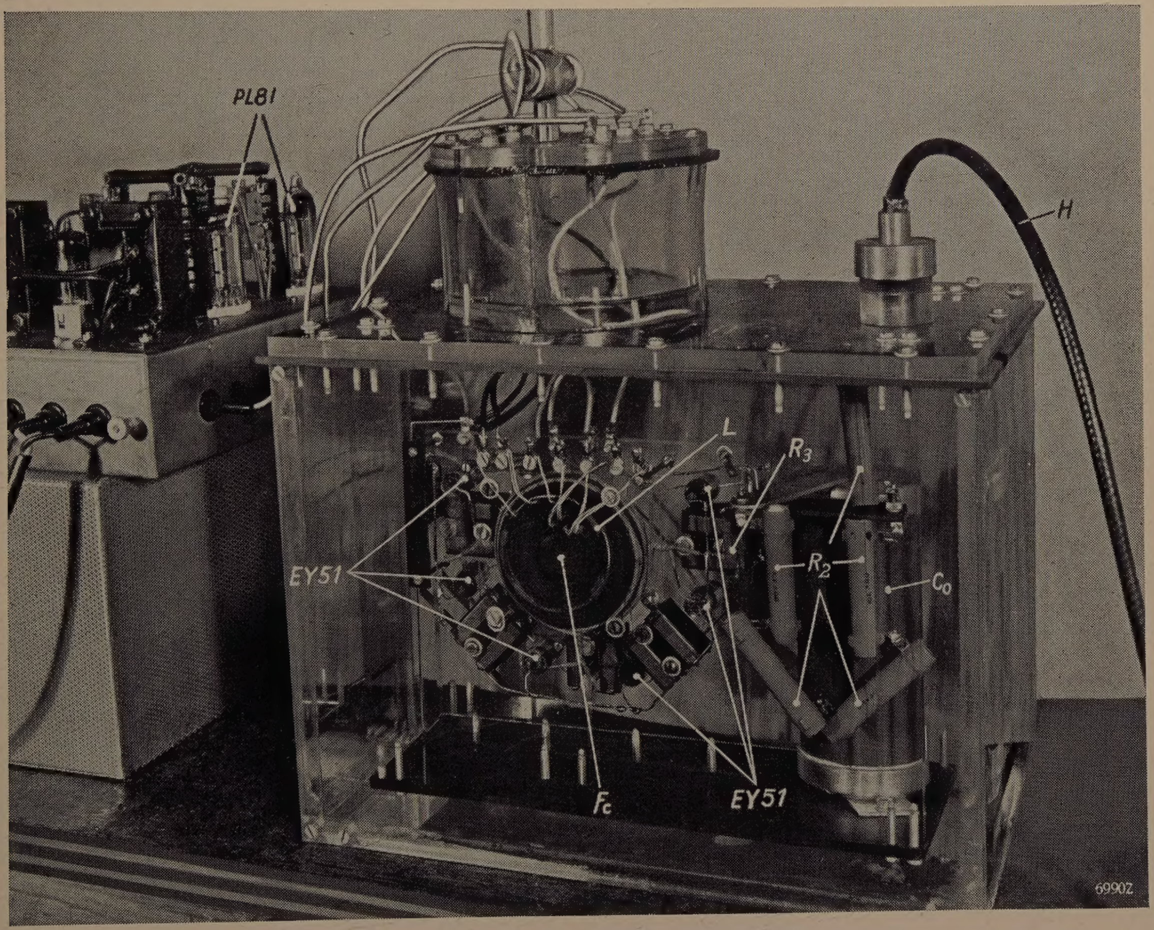

Fig. 13. Experimental H.T. generator to deliver 50 kV, 1.5 mA. Left-hand top: chassis with oscillator valves (PL 81) and voltage control circuit. Centre: oil-filled container with oscillator coil L (and Ferroxcube core Fc) and the six cascade stages of the rectifier (with diodes EY 51), mounted round the coil; reservoir capacitor C_0, protecting resistors R_2 and R_3. H is the H.T. cable for connection to the cathode-ray tube. The container is made of "Perspex", so that the internal components can be observed.

Fig. 14 shows the characteristics of the output voltage V_0 and the total anode current I_a derived from a 1000 volt direct-voltage source, as functions of the load current I_0. In contrast with the first example, the current I_a rises on an increasing load.

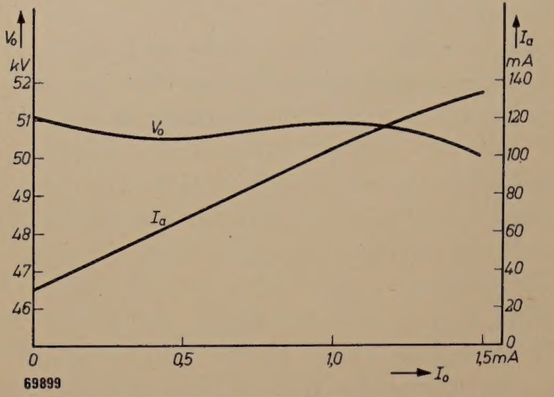

Fig. 14. Direct voltage V_0, and total input anode current I_a drawn from a 1000 V source, as functions of the load current, I_0, of the generator shown in fig. 13.

On full load I_a = 135 mA, and the efficiency is then:

$$\frac{50000 \times 1.5 \times 10^{-3}}{1000 \times 135 \times 10^{-3}} \times 100\% \approx 56\%.$$

The voltage control circuit already described ensures that the internal resistance (measured statically) will be sufficiently low. In television pictures, however, fairly large bright areas may occur in which the beam current would greatly exceed the value of $I_{0\,\mathrm{max}}$ and, in order to prevent the acceleration voltage from dropping to too low a level, it is advisable to connect a reservoir capacitor to the output terminals. Seeing that exceptionally high standards were set for the picture quality of the projector for which this H.T. generator was designed, the actual reservoir capacitor used had a fairly large value (10,000 pF), but in many cases a smaller capacitance would suffice.

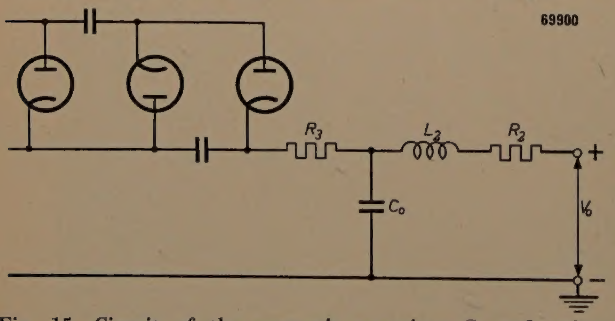

Fig. 15. Circuit of the reservoir capacitor C_0 and safety resistors R_2 and R_3 in the generator depicted in fig. 13. L_2 = self-inductance of the resistor R_2. On the left: part of the cascade circuit.

The large quantity of energy stored in this capacitor would prove detrimental in the event of breakdown in the cathode-ray tube which, albeit sporadically, is liable to happen. To prevent possible damage, a resistor R_2 is provided (figs. 13 and *15*). This is a wire-wound resistor the self-inductance of which (0.5 mH) is sufficient to limit the current from the reservoir capacitor to some tenths of an ampere in the event of a flashover of very short duration (10^{-8}sec). If the duration is longer its resistance of 50,000 Ω limits the current to 1 A. A second resistor (R_3 = 0.5 MΩ) serves to limit the charging current of the capacitor C_0 when the circuit is switched on, thus protecting the diodes. The combination of R_3 and C_0 moreover acts as a smoothing filter.

The effect of the resistor R_2 can best be demonstrated by connecting a spark-gap to the generator; with-out the resistor R_2 each flashover produces a sharp crack, whereas with the resistor only a faint click is heard. The experimental generator proved well able to withstand such tests.

In view of the efforts made to keep the internal resistance as low as possible it may appear strange to increase the resistance by as much as 0.5 MΩ, but this value is virtually low in comparison with the internal resistance that would be encountered in the absence of any voltage control (about 10 MΩ). The extra resistance R_3 therefore has little effect on the final result.

The development of this immersed generator has been a source of valuable experience against the time when units for even higher voltages may be required.

Summary. Television pictures of large dimensions having at the same time high brightness and definition can be obtained only by means of tubes operating with very high acceleration voltages. Present-day receivers working on the projection principle employ 25 kV, but equipment developed in the Philips Laboratories at Eindhoven producing a picture of 3 m × 4 m uses 50 kV. Four methods of generating such high voltages are reviewed and one of these is described in detail, namely one in which an oscillator, preferably having a coil with Ferroxcube core, delivers an alternating voltage of 20 to 30 kc/s, this being rectified by a cascade circuit. This proves to be the best arrangement to meet the conditions imposed on an H.T. generator for the purpose in question, namely constant direct voltage from no-load to full-load conditions, with a rapid fall in potential when full load is exceeded. The rectifier and oscillator in such systems are discussed, as also methods of ensuring a low internal resistance. Examples are given in relation to two experimental generators (50 kV, 0.45 mA and 50 kV, 1.5 mA).